Bulletin

of

The Geological Society of America

VOLUME 58 July 1947 NUMBER 7

CONTENTS

PAGES

Cenozoic physiographic history of the Front Range, Colorado. By Ernest E. Wahlstrom 551–572

Chemical analyses and calculated modes of the Oliverian magma series, Mt. Washington quadrangle, New Hampshire. By Marland P. Billings and John C. Rabbitt 573–596

Cambrian rocks of northeastern Stevens County, Washington. By Charles D. Campbell 597–612

Holarctic mammalian faunas and continental relationships during the Cenozoic. By George Gaylord Simpson 613–688

Subscription $10 per year.

Publication Office: Mt. Royal and Guilford Aves., Baltimore 2, Md.

Communications for publication should be addressed to The Geological Society of America, Dr. H. R. Aldrich, Secretary, 419 West 117th Street, New York 27, N. Y.

NOTICE.—Four weeks notice of change of address is necessary. In accordance with the rules established by the Council, claims for non-receipt of the preceding number of the Bulletin must be sent to the Secretary of the Society within three months of the date of the receipt of this number in order to be filled gratis.

Entered as second-class matter in the Post-Office at Baltimore, Md., under the Act of Congress of July 16, 1894.

Accepted for mailing at special rate of postage provided for in Section 1103 Act of October 3, 1917, authorized on July 8, 1918.

PAPERS IN PRESS FOR FORTHCOMING ISSUES

ARCHEAN GEOLOGY OF THE TUREU DISTRICT, SOUTHWESTERN FINLAND. By Anna Hietanen

BLACK HAND SANDSTONE AND CONGLOMERATE IN OHIO. By Karl Ver Steeg

ELEMENTS OF DIASTROPHIC HISTORY OF NORTHEASTERN VENEZUELA. By Clemente Gonáles de Juana

CORAL REEFS OF THE EAST INDIES. By J. H. F. Umbgrove

DELINEATION OF PARALLEL FOLDS AND MEASUREMENT OF STRATIGRAPHIC DIMENSIONS. By John B. Mertie, Jr.

OÖLITE DEFORMATION IN THE SOUTH MOUNTAIN FOLD, MARYLAND. By Ernst Cloos

BIOGEOCHEMICAL PROSPECTING FOR COPPER AND ZINC. By H. V. Warren and C. H. Howatson

This paper is accompanied by a colored geologic map, 36 by 45 inches, scale 1:50,000. A limited number of copies of the map, unfolded and in tubes, will be available. Price 50 cents apiece prepaid. Orders should be accompanied by remittance.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 58, PP. 551–572, 7 FIGS. JULY 1947

CENOZOIC PHYSIOGRAPHIC HISTORY OF THE FRONT RANGE, COLORADO

BY ERNEST E. WAHLSTROM

CONTENTS

	Page
Abstract	551
Introduction	551
General statement	551
The Front Range	552
Acknowledgments	553
Previous work	553
Critical relationships	555
General statement	555
Bevelled igneous bodies	555
Front Range structure	559
Glacial erosion and deposition	561
Rate of canyon cutting	567
Differential erosion	568
Pleistocene uplift of the Front Range	568
Erosion of warped or faulted uplifted surfaces	569
Summary of conclusions	570
References cited	571

ILLUSTRATIONS

Figure	Page
1. Index map	553
2. Plan and profile of Specimen Mountain area	558
3. Major faults of the central part of the Front Range	560
4. Glacial deposits in the Audubon-Albion region	562
5. Glacial deposits in the Tungsten Mountain area	563
6. Comparative profiles	567
7. Development of interfingering remnants of erosion surfaces	570

ABSTRACT

The multiple-peneplain hypothesis for the Front Range of Colorado is rejected as unsatisfactory. Re-examination of all available types of evidence indicates that remnants of only one extensive pre-Pleistocene old-age surface are present. This surface probably reached its maximum development in late Pliocene or early Pleistocene. Uplifts initiated in late Pliocene or early Pleistocene accelerated erosional processes which resulted in deep dissection of the uplifted surface during later Pleistocene to produce the modern canyons and valleys.

INTRODUCTION

GENERAL STATEMENT

The Front Range of Colorado has been studied as intensively and extensively by geologists and physiographers as any other comparable mountainous area of North America. A variety of rock types, geological structures, and ore deposits, all rela-

tively well exposed, have permitted the reconstruction of the geologic history in considerable detail. With the solution of many of the larger problems of subsurface geology nearing completion, in recent years an increasing amount of attention has been paid to the history of the development of the surface features. Several attempts have been made to weave the physiographic history into the sequence of events recorded in the rocks and structures of the mountains and in the sedimentary deposits of the adjacent plains.

The Southern Rocky Mountains, of which the Front Range is an important unit, are the end result of a complex series of geologic processes beginning in the pre-Cambrian, but the present mountains are the product of repeated uplifts and erosion which were initiated during the Laramide revolution at the close of the Cretaceous and the beginning of the Cenozoic. Consideration of the recent physiographic history is thus limited to a study of the surface forms which developed during the Cenozoic.

In previous studies special attention has been given to the extensive erosion surfaces in the intermediate and higher parts of the range. Accordance of summit levels over extensive areas has led to the acceptance by most observers of the concepts of single or multiple Cenozoic peneplains. Much controversy has been engendered, and it is not yet settled whether the accordant surfaces actually are the remains of a peneplain or peneplains or have formed by processes other than those implied by the term peneplain. Moreover there is no unanimity of opinion as to the number, ages, and correlation of the surfaces, whether they are regarded as uplifted dissected peneplains or not. The pendulum of thought has swung from one extreme to the other. One of the early observers in the area (Davis, 1911) saw evidence for the presence of only one extensive uplifted surface. Recently, Van Tuyl and Lovering (1935) presented arguments for the existence of as many as five and possibly eight peneplains, three berms or "surfaces", and five terraces.

The present writer has made studies which suggest that modification of the views held by earlier workers is necessary. This paper brings together certain observations, inferences, and conclusions that must be considered by anyone attempting to construct the Cenozoic physiographic history of the Southern Rocky Mountains and in particular that of the Front Range.

THE FRONT RANGE

The Front Range of Colorado (Fig. 1) extends for approximately 180 miles from the Arkansas River where it enters the Canyon City embayment north nearly to the Colorado-Wyoming State line. North of the State line the Front Range continues in a narrow belt of subdued mountains comprising the Laramie Range. To the west the Front Range is bounded in part by North, Middle, and South parks and to the east by the High Plains.

Hogbacks are conspicuous in the foothills along the east side and give way to the west to a gradual rise in the land surface starting at an elevation of about 7500 feet and reaching an average elevation of about 12,500 feet. Along the crest of the range many peaks reach elevations of about 13,000 to 14,000 feet or slightly more. Pikes Peak near the southern end is an isolated outlying peak, standing close to the eastern limit of the Front Range.

ACKNOWLEDGMENTS

The writer is deeply indebted to many individuals with whom he has discussed details of the geologic and physiographic history of the Front Range. Many stimulating ideas have come from conversations with N. M. Fenneman, T. S. Lovering, Louis Ray, Lincoln R. Page, and others.

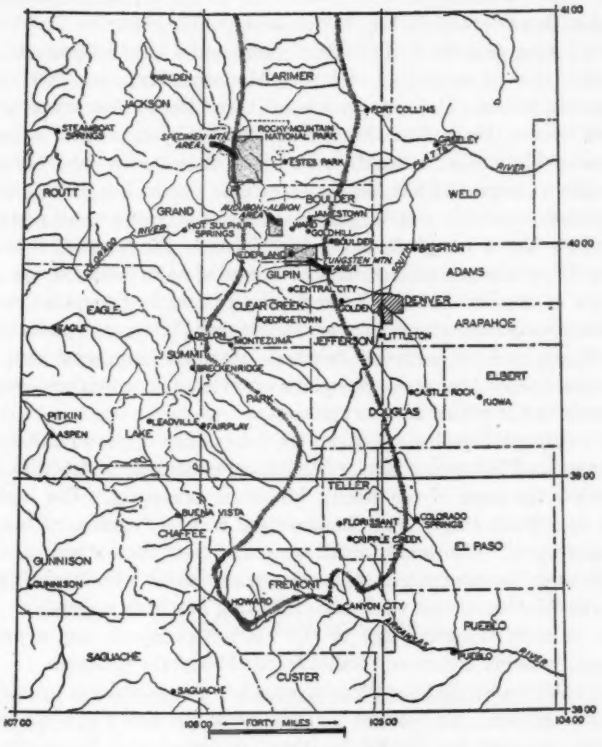


FIGURE 1.—*Index map*
Showing outlines of Front Range and areas described in this report.

The manuscript was read by P. G. Worcester, W. O. Thompson, and R. W. Wilson, all of the Department of Geology at the University of Colorado. Each made valuable suggestions and criticisms. The conclusions reached in the paper, however, are the writer's own and do not necessarily reflect the opinions of any of the persons mentioned above.

PREVIOUS WORK

The first critical appraisal of the physiography of the Front Range was made by W. M. Davis (1911). He wrote of the Front Range as a "two cycle" mountain mass, one in which the observed features may be explained as a result of reduction of the land surface to a broad rolling plain followed by uplift and dissection. He

DETROIT PUBLIC LIBRARY

regards the accordant summits as remnants of a differentially upwarped peneplain which he referred to as the "Highland peneplain of the Front Range".

Finlay (1916) in his work on the Colorado Springs Folio of the U. S. Geological Survey noted the remarkable accordance of summit levels at about 9500 feet in the area west and north of Pikes Peak. He also observed high accordant levels to the west. He regarded the upper and lower levels as the faulted segments of a single peneplain which was completed by the close of the Oligocene.

In the following year W. T. Lee (1917) published a brief semipopular description of the geology and physiography of Rocky Mountain National Park. He was the first to use the terms "Flat-top peneplain" and "Rocky Mountain peneplain" in the modern sense. He named the Flattop peneplain after the Flattop mountain area in Rocky Mountain National Park, where there are several broad accordant summit levels at about 12,500 feet in elevation. Later Lee (1923) described the two peneplains more fully and suggested the possibility of a third peneplain at the elevation of the top of Long's Peak (el. 14,255 feet). He reasoned that the Flattop and Rocky Mountain peneplains must be regarded as of different age because flat valley floors at the level of the lower Rocky Mountain peneplain surface extend back into the area occupied by remnants of the higher Flattop peneplain. He regarded the Front Range as a "three cycle" mountain mass and suggested that the erosion producing the Rocky Mountain peneplain provided the sediments comprising late Tertiary beds in the plains area to the east.

In 1925 Little published a discussion of the erosion cycles of the Front Range. In addition to the Flattop and Rocky Mountain peneplains, he described two erosion surfaces below the level of the Rocky Mountain peneplain. The higher of these he named the "Park stage" and characterized it as a "surface of mature to late mature topography." Lower than the surface of the "Park stage" and between it and the present canyon-cutting stage, he recognized a "Fountain Creek stage". He consulted Mather in this work and, following Mather's suggestions, he ascribed an Eocene or early Oligocene age to the Flattop peneplain and a probable mid-Tertiary age, possibly Pliocene, to the Rocky Mountain peneplain.

Mather (1925) stated that the Flattop peneplain was completed by early Oligocene and was then uplifted. He thought that erosion of the higher portions of the surface provided the material for the White River, Arikaree, and Nussbaum formations to the east of the Front Range. According to this concept the sediments were deposited on a surface which was coextensive with the uplifted surface. Mather suggested that erosion of the uplifted Flattop peneplain continued until late Pliocene or early Pleistocene when the mountains were again uplifted.

In 1931 Fenneman accepted the notion of two peneplains, one at an altitude ranging from about 8000 feet near the foothills to about 10,000 feet around the residual older mountains, and another 1500 to 2000 feet higher, the Flattop peneplain of Lee. Fenneman objected to the term "Rocky Mountain peneplain" and suggested that "South Park peneplain" be used instead. Fenneman agreed with Lee's suggestion that the Rocky Mountain peneplain surface is of the same age as the surface over the Pliocene sediments now covering the High Plains.

Worcester (1931) extended the Rocky Mountain and Flattop peneplains into

adjacent mountainous areas. He correlated the Front Range surfaces with similar surfaces of known age in the Beartooth Mountains of Wyoming and suggested on the basis of these correlations that the Flattop peneplain is post-mid-Eocene and pre-mid-Miocene. He accepted the view that the remnants of the Rocky Mountain peneplain are Miocene or Pliocene in age. Later (1939) he expressed essentially the same convictions.

Behre (1933) stated that it was probable that the 12,000-foot erosion level in the Arkansas Valley region near the southern end of the Front Range is the equivalent of the Rocky Mountain peneplain.

In a study of the geomorphic development of the Arkansas River Valley at the southern end of the Front Range, Powers (1935) challenged the mid-Tertiary age previously assigned to the Rocky Mountain peneplain by some writers. He correlated with the Rocky Mountain peneplain a surface bevelling tilted Pliocene sediments. In the same year Van Tuyl and Lovering (1935) published a detailed account of the physiographic development of the Front Range. These writers claimed that they could recognize at least five and perhaps eight peneplains, three berms or "surfaces", and five terraces ranging in age from Eocene to the present. Rich (1935) vigorously attacked the fundamental premises on which Van Tuyl and Lovering based their conclusions and suggested that the accordant levels of the Front Range may be the residuals of a surface from which sediments have been stripped or that pedimentation has been active in the development of many of the broad smooth surfaces regarded by Van Tuyl and Lovering as peneplain remnants. Van Tuyl and Lovering (1935) in a reply to Rich's assertions reaffirmed their previously expressed views.

Atwood and Atwood (1938) in a regional study accepted the concept of Flattop and Rocky Mountain peneplains and correlated the Rocky Mountain peneplain of the Front Range with similar surfaces in other parts of the Rocky Mountains.

CRITICAL RELATIONSHIPS

GENERAL STATEMENT

The dating and correlation of the erosion surfaces in the Front Range, whether they are peneplains or not, is one of the most important problems that must be solved before the physiographic history can be established. In this paper the criteria used for establishing two or more peneplain surfaces are scrutinized. The relationships between the supposed peneplains and the igneous rocks and structures they bevel, and the significance of deposits of glacial till on both the Rocky Mountain and Flattop surfaces are discussed.

BEVELLED IGNEOUS BODIES

The igneous rocks of the Front Range fall into two categories based on broad age distinctions. The pre-Cambrian rocks form large batholithic masses of granite and granodiorite. The Tertiary igneous rocks occur in part as stocks, dikes, and sills injected into the pre-Cambrian rocks, locally into Paleozoic and Mesozoic sediments, and in part as extrusive surface lava flows and pyroclastics. The present investigation is concerned chiefly with the Tertiary rocks, and in particular with the

extrusive rocks, for only these are significant in the interpretation of the Cenozoic physiographic history.

The largest bodies of Tertiary igneous rocks are stocks which lie in a belt extending from Jamestown, in Boulder County, diagonally southwest across the Front Range to Montezuma, in Summit County. Attending these stocks are numerous small satellitic intrusive bodies. Abundant evidence indicates that most of the stocks were intruded a short time after the initiation of the Laramide uplift of the Front Range. Generally the larger stocks are of Paleocene and early Eocene age. Smaller stocks of probable mid-Tertiary age are exposed in Boulder County and elsewhere. The extrusive flows and pyroclastics are of probable mid-Tertiary age and are more erratic in their distribution than the stocks. The most notable localities are Specimen Mountain in Rocky Mountain National Park, where a dissected volcano, is exposed; Florissant, near Pikes Peak, the site of extensive tuff and ash beds; and Cripple Creek. The Florissant and Cripple Creek localities enter into the present discussion because they aid in establishing the mid-Tertiary age of the extrusive igneous rocks of the Front Range. Gazin (1935) expressed the opinion that the Florissant beds are of Oligocene age. R. W. Wilson (personal communication) on the basis of a study of an oreodont concurs with Gazin. Loughlin and Koschmann (1935) state that the volcano, now largely eroded, which supplied the Cripple Creek flows and pyroclastics is of approximately the same age as the Florissant beds. In both places physiographic evidence indicates that the volcanics predate the Rocky Mountain peneplain.

Specimen Mountain (Wahlstrom, 1944; Wegemann, 1944) is located at the crest of the Front Range in Rocky Mountain National Park and yields particularly significant data. Specimen Mountain is the eroded plug of a large explosive volcano which erupted a succession of lava flows, agglomerates, and ash beds. These are preserved in part on the north, west, and south sides. The lava flows extended for miles in all directions from the central conduit. An eroded remnant of one of these flows is exposed near Iceberg Lake about 3 miles southeast of the top of Specimen Mountain. The Iceberg Lake remnant is preserved by virtue of the fact that it filled a prevolcanic valley cut into pre-Cambrian rocks and was partly protected from subsequent erosion. The present level of the floor of the Iceberg Lake flow is about 11,500 feet. Projection of the floor back toward the plug at Specimen Mountain suggests that the crest of the cone originally built up by the lava flows and pyroclastics extended as much as 3000–5000 feet above the present top of the mountain (el. 12,482 feet).

The topography of the surface on which the lava and pyroclastics were laid down was exceedingly rugged as is shown in Cache la Poudre valley. The valley of the northeasterly flowing Cache la Poudre River lies between the Iceberg Lake remnant and Specimen Mountain. The floor of the valley is about 1000 feet lower than the flow at Iceberg Lake. The valley was present before the Specimen Mountain volcano came into existence and was gradually filled with lava and pyroclastics until the topography was sufficiently smoothed out to permit lava to flow from the central vent to the Iceberg Lake area. That Cache la Poudre valley existed prior to the initial eruptions of Specimen Mountain is proved by the presence of a veneer

of pyroclastics and lava flows on the floor and southeast side of the valley and the presence of a thick pile of dissected flows and pyroclastics on the northwest side.

The modern valley of the Cache la Poudre at its headwaters is an exhumed valley formed by the postvolcanic excavation of easily eroded volcanic rocks which filled a deep prevolcanic valley. The valley cannot be explained as a downfaulted block because identifiable layers of volcanic material can be traced across the valley floor from one side to the other without interruption. Additional evidence supporting the belief that the prevolcanic topography was rugged is found on the northwest side of Specimen Mountain. Here lava flows and pyroclastics filled deep prevolcanic canyons at the headwaters of the Colorado River. Spock (1928, p. 215) in a study which included field examinations of the Tertiary igneous rocks of the rugged Never Summer Mountains, which lie across the canyon at the headwaters of the Colorado River 3 to 4 miles west of Specimen Mountain, states that the discordance in altitude of the basal contacts of the lava flows amounts to nearly 1000 feet in the Cameron Pass region. He concludes that the lavas poured out on a surface of high relief. Elsewhere he (1928, p. 183) states that the lava flows came from the east (*i.e.*, from the direction of Specimen Mountain). Examination of the exposed flows in the Never Summer Mountains by the present writer substantiates Spock's conclusions.

Exact determination of the age of the Specimen Mountain volcano is difficult, but consideration of the available evidence suggests that it is mid-Tertiary, probably late Oligocene and Miocene. The volcano may have been active at the same time that Oligocene volcanoes were active in the Florissant area in the southern part of the Front Range. However, Specimen Mountain volcano is better preserved than any other extruded igneous mass in the Front Range. Considering that the rocks in the flanking flows and pyroclastics are very easily eroded, possibly all or part of the Specimen Mountain volcanic rocks are younger than those at Florissant.

Additional evidence helping to date the Specimen Mountain volcano is found in the Tertiary sediments on the east and west sides of the Front Range. In northern Colorado near the Wyoming State line and in northeastern Colorado according to R. W. Wilson (personal communication) the White River formation of Oligocene age and the overlying Arikaree and Ogallala formations of Miocene and late Miocene and Pliocene age, respectively, contain abundant pyroclastic volcanic material, chiefly ash. It is not certain whether the ash in the Ogallala formation is original or reworked material from the underlying formations. In any event, the presence of the ash in the White River and Arikaree formations points to abundant explosive volcanic activity in the northern part of the Front Range during Oligocene and Miocene. About 12 miles northwest of Specimen Mountain, in North Park, clastic volcanic materials resembling those in Specimen Mountain are found in the North Park formation of Miocene (?) age (Wilmarth, 1938). Abundant volcanic materials, possibly derived from Specimen Mountain or a related source, are found in lower Miocene sediments (Lovering, 1930) exposed near Granby, about 25 miles south of Specimen Mountain. Inasmuch as the Specimen Mountain volcano was the major center of explosive volcanism in the northern Front Range, it undoubtedly contributed much volcanic material to the Tertiary sediments.

The Iceberg Lake lava remnant is near the west end of Trail Ridge. The relatively flat, rolling top of Trail Ridge has been considered a typical remnant of the Flattop peneplain. The Flattop Mountain area, the type area, is south of Trail Ridge only about 8 miles across Forest Canyon.

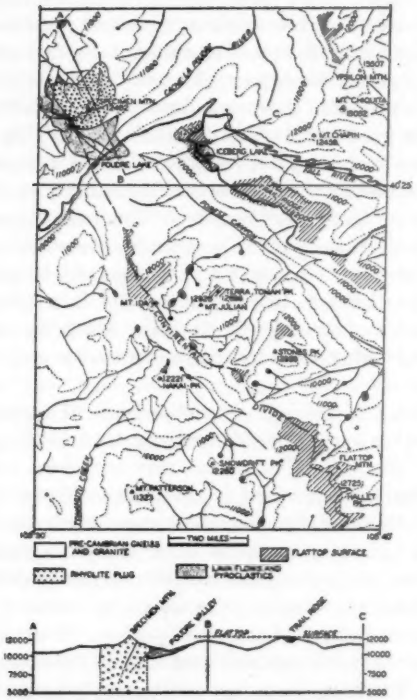


FIGURE 2.—*Plan and profile of Specimen Mountain area*
Showing Specimen Mountain volcanics and remnants of Flattop peneplain.

The surface at the top of Trail Ridge bevels the lava remnant at Iceberg Lake (Fig. 2). However, the surface that cuts across the lava remnant must be post-Specimen Mountain volcano and therefore post-mid-Tertiary and cannot be regarded as the remnant of an Eocene or even an Oligocene peneplain. The question arises as to whether the surface truncating the Iceberg Lake lava remanant is part of the surface referred to by previous writers as the Flattop peneplain or whether the Flattop surface was buried by the volcanic rocks erupted from Specimen Mountain. Suggestive evidence is found at the lower contact of the Iceberg Lake flow where lava rests on a soil zone which, in turn, grades downward into weathered gneiss. This relationship might be interpreted as connoting a prelava surface in late maturity or old age formed during the Eocene or Oligocene. If a late-mature or even an old-age surface existed prior to the eruption of the lava, this surface was deeply dissected by steep-walled canyons. This conclusion is implied in the statements that the

prevolcanic surface was one of considerable relief. If the region blanketed by the volcanics was rugged, it is logical to assume that near-by areas also were rugged because the same type of basement rock and the same erosional environment existed in these areas.

The remnants of the so-called Flattop peneplain in the type area a few miles south of Iceberg Lake are broad, gently rolling surfaces a mile or more across, bounded and separated by cliff-walled glacial gorges. The summit of Trail Ridge itself is a broad rolling surface that in places is a mile wide. If it is assumed that the present remnants of the Flattop surface in the type area correlate with possible remnants of a prelava mature or old-age surface, the conclusion is that the rugged prelava topography has persisted, with the preservation of the flat remnants through the long period of time occupied by the development of the Specimen Mountain volcano, the reduction of Specimen Mountain to its present form, and the intensive stream and glacial erosion of the Pleistocene. The Flattop remnants might suggest exhumation from beneath a blanket of volcanic materials because of local evidence, but the suggestion is not confirmed in other parts of the Front Range where remnants of the Flattop surface abound, and there is no evidence of the former presence of a protective cover. In view of this discussion the only logical conclusion that can be reached in the mind of the writer is that the surface cutting across the Iceberg Lake lava remnant is of the same age and formed in the same manner as the surfaces to the south that have been regarded as typical remnants of the so-called Flattop peneplain.

In the foregoing discussion the writer has expressed his reasons for believing that there is no valid evidence for assuming the existence of remnants of an Eocene or Oligocene peneplain in the Front Range. However, if the data given above are not considered as conclusive, there are other types of corroborative evidence leading to the same conclusion. This evidence is summarized in succeeding pages.

FRONT RANGE STRUCTURE

The uplift of the Front Range during the Laramide revolution resulted in the development of a complex pattern of folds and faults. Some of the major faults show thousands of feet of displacement (Fig. 3). In the northeastern part of the range the dominant structures are northwesterly trending faults of large displacement described by Lovering (1932) as "breccia reefs." Some of these faults are as much as 15 miles in length and cut across and offset the sediments along the east side of the range and the pre-Cambrian gneiss and granite in the core of the range. The movement along these faults was largely horizontal although a strong vertical component is locally evident.

In the west-central part of the Front Range, near the crest and roughly parallel to it, is another strongly faulted zone. A typical fault in this zone is the Berthoud Pass fault which extends from near Jasper Lake south-southwest for about 26 miles to the vicinity of Loveland Pass. The amount of displacement along the fault zone is not known, but it probably is of the order of thousands of feet.

In the vicinity of Dillon, on the west side of the central part of the Front Range, the Williams Range thrust fault is exposed. This fault dips about 30°E. and has

resulted in superposition of pre-Cambrian gneiss on Pierre shale of Cretaceous age. The horizontal component of displacement is measured in miles.

In the southern part of the Front Range large faults have not been mapped in as great detail as in the central part of the Front Range, because, except for those in the Cripple Creek area, there are no economic deposits warranting detailed regional studies.

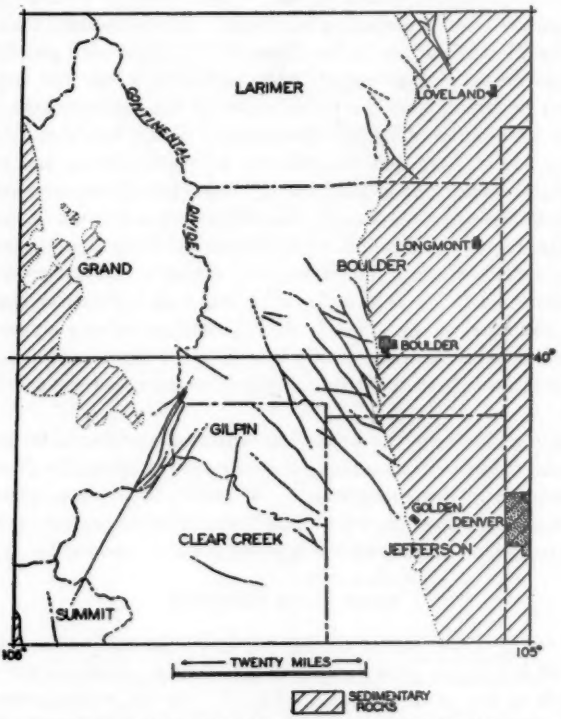


FIGURE 3.—*Major faults of the central part of the Front Range*

The major faults and associated minor faults were in existence before the intrusion of the early Tertiary Montezuma, Audubon-Albion, and related stocks. This relationship is evident in many places where the igneous rocks crosscut the pre-existing fault pattern. Many of the faults, both major and minor, show evidence of repeated additional movements subsequent to the intrusion of the stocks. The later movements probably were contemporaneous with repeated uplifts of the Front Range during later Tertiary and, perhaps, part of Pleistocene.

If, as seems likely, the structural adjustment of the Front Range in response to post-Eocene orogenic forces took place at least in part by movements along both major and minor faults, the possibility of preservation of a series of accordant summit levels of Eocene or even Oligocene age seems remote. Powers (1935, p. 189) drew

a cross section which indicates a fault of considerable displacement involving Pliocene sediments near Howard in the southern part of the Front Range. Probably this is but one example of similar faults many of which are not located so as to permit definite age assignment. Stark, Johnson, Behre, *et al.* (1935) mention late Tertiary block faulting in South Park, which lies on the west side of the southern part of the Front Range.

Lovering (1935, p. 1301) makes the following statement:

> "In the Fraser Quadrangle, faults trending north-northeast involve lower Miocene sediments. A fault of this trend passes through Riflesight Notch, three miles east of West Portal, in the western portion of the Central City Quadrangle. This fault is believed to continue south-southwestward into the Berthoud Pass area. It dips west at an angle of about 50 degrees and is marked by a zone of sheared rock. To the west of the fault the Flattop and Green Ridge surfaces have almost their normal elevations and are not appreciably warped. To the east, however, a smooth slope rises steeply to elevations well above that of the upper Flattop surface where it is preserved just west of the fault (Pl. 108, fig. 2). This steep slope is probably due, in large part, to the weathering and erosion of the sheared rock of the fault zone. It merges smoothly with remnants of the upper Flattop surface which appears to have been upwarped during the faulting."

Loughlin and Koschmann (1935, p. 240–242) noted the presence of several post-volcanic faults in the Cripple Creek district and state that one fault at least offsets a postphonolite erosion surface. The volcanics are generally regarded as of Oligocene or Miocene age.

Many of the ore deposits throughout the Front Range exhibit slight postore movements. Generally these movements are parallel to the veins and are evidenced by dragged-out, brecciated, and slickensided vein minerals. Although the movement along an individual vein generally is small, the aggregate movement in a heavily mineralized district is probably large. In the northern part of the mineral belt, especially in Boulder County, the small displacements appear to reflect larger displacements in large, through-going faults. It is difficult to date these dislocations, but it seems reasonable to assume that some of them formed concomitantly with middle and late Tertiary uplifts of the Rocky Mountains.

In the central part of the Front Range, remnants of the Flattop peneplain slope eastward and seem to be continuous with the Rocky Mountain peneplain but are more steeply inclined. Differential warping plus some fault movement may account for the observed features. In other areas remnants of the 12,000-foot surface bear a steplike relationship to the Rocky Mountain peneplain surface. This relationship exists, for example, at the east end of Niwot Ridge near Ward. However, the rocks here are shattered by strong faults, and possibly the steplike relationship is the result of faulting and does not signify two separate cycles of erosion.

GLACIAL EROSION AND DEPOSITION

The gorges of the higher portions of the Front Range show the effects of typical Alpine valley glaciation. Most of the major valleys terminate headward in deep bowl-shaped cirques, and the skyline along the crest of the range is in many places characterized by an intricate pattern of jagged, serrate ridges. Glacial erosion has been greatest in the region of the accordant summits that have been referred to the Flattop "peneplain", and many remnants of this surface have been all but destroyed. Locally the glaciers have scoured valleys below the level of the Rocky Mountain peneplain.

The valley glaciers record the fact that canyons cut below the levels of the Flattop and Rocky Mountain surfaces were repeatedly glaciated during the Pleistocene.

Glacial deposits which are present on the interstream summit areas and are not related to the valley glacial deposits are of considerable significance. In recent

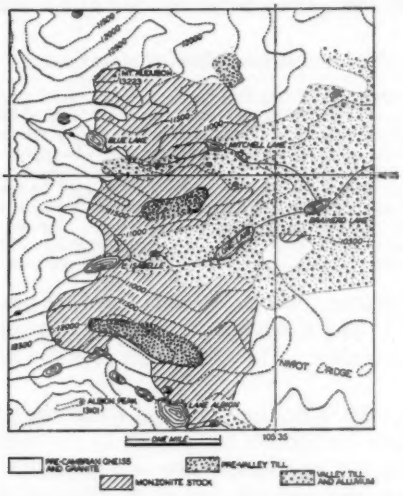


FIGURE 4.—*Glacial deposits in the Audubon-Albion region*
Showing isolated till deposits on high interstream areas.

years abundant evidence has been discovered to show that the Front Range was glaciated by ice which was not confined to the present valleys, but spread out as an ice sheet over the higher parts of the range. Accumulating observations indicate that this glaciation is Pleistocene in age, almost certainly pre-Wisconsin. Atwood and Atwood (1938) mention several localities in the Front Range and adjacent mountainous areas where deposits of till have been discovered on relatively flat interstream areas in positions such that they could not have been deposited by the glaciers which moved down the adjacent valleys. The present writer has studied similar glacial deposits in Boulder County and has arrived at conclusions which have an important bearing on the interpretation of the pre-Pleistocene as well as the Pleistocene physiographic history.

On Niwot Ridge between Albion valley and the valley of Lake Isabelle and resting on the bevelled surface of the Audubon-Albion stock at elevations ranging from 11,500 to 12,000 feet is a deposit of till consisting of large boulders of pre-Cambrian granite and gneiss embedded in unsorted finer material (Fig. 4). The till is exposed in cross section at the top of the clifflike walls of Albion valley and in places is as much as 50 feet thick. The surface of the till shows the effects of frost action, and polygonal rock patterns consisting of angular frost-shattered boulders and soil are well developed, but the deeper parts of the till are unaffected. Solifluction on the rolling surface of the till has locally produced morainelike ridges as much as 20 feet high. Some of the till has slumped to form rock streams blanketing the upper slope of the

south side of the valley of Lake Isabelle. The depth of weathering of the boulders is to a large extent dependent upon their mineral composition but is greater than in corresponding boulders in the glacial deposits in the valleys.

Similar till deposits are found on the rolling high surface north of the valley of Lake Isabelle and on benches on the side of Mount Audubon at an elevation of

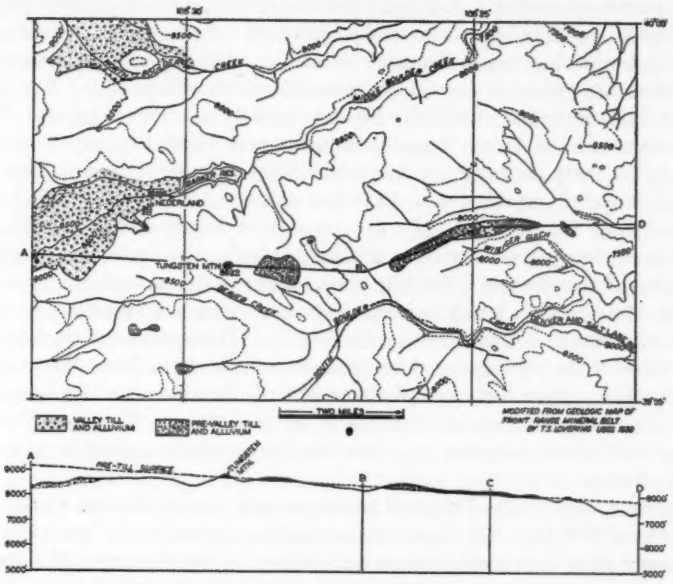


FIGURE 5.—*Glacial deposits in the Tungsten Mountain area*

about 12,000 feet. In each exposure the character of the material and its position are such that a probable glacial origin cannot be denied. To the south and north of the Audubon-Albion region other deposits of unconsolidated boulder conglomerate are found in corresponding positions on the high rolling summits of east-trending ridges at elevations averaging between 11,500 to 12,000 feet, but the glacial origin of these deposits is not so easily established as in the Audubon-Albion region because the component materials generally consist of pre-Cambrian rocks similar to those on which they rest. Therefore it is more difficult to prove that the material has been transported to its present location and is not residual. Similar occurrence and physical characteristics make it possible safely to correlate these deposits with those on Niwot Ridge.

These high till deposits are at the elevation of the Flattop surface and presumably were deposited on it.

Another significant deposit regarded as glacial till by the writer is found on Tungsten Mountain about 2 miles southeast of Nederland (Fig. 5). This material forms a capping layer on the top of a low peak (el. 8922 feet) standing up about 400 feet above the surrounding region. The layer is approximately 50 feet thick and appears

to rest on a relatively smooth surface of weathered gneiss. Van Tuyl and Lovering (1935) interpreted the Tungsten Mountain deposit as lower Oligocene stream gravel accumulated on the floor of a valley but admit that it closely resembles till. The possibility that Van Tuyl and Lovering's interpretation is correct cannot be overlooked. They suggest that the gravel and large boulders were deposited by a swiftly flowing mountain stream. Abundant pebbles of a quartz monzonite porphyry in the deposit appear to have been transported from a stock of the same rock at Ute Mountain, 5 miles due west of Tungsten Mountain. The implications of these statements, when fully explored, are, to say the least, somewhat surprising. The "swiftly flowing mountain stream" must have been confined by a valley or canyon. Present major streams in the Front Range in canyons over 1000 feet deep during flood periods do not carry for any great distance boulders as large as some of those in the Tungsten Mountain deposit (up to 15 feet in diameter). Accordingly the boulders must have come from the walls of a canyon or were transported by a swift stream flowing down a canyon of very steep gradient, or both. In any event mountainous topography of considerable relief is implied. Boulder deposits similar to those on Tungsten Mountain are found in isolated remnants in a narrow belt extending for about 5 miles east of Tungsten Mountain (Fig. 5). These remnants reach to within about 5 miles of the hogbacks marking the eastern limit of the Front Range and cap hills and ridges. Near the east end of the belt the deposits contain a greater proportion of rounded boulders and less coarse material than on Tungsten Mountain, but fragments of the porphyry from Ute Mountain, and occasional large boulders are still present.

The present relief in the Tungsten Mountain area and in the area to the east is of the order of 1000 feet. The mountains and ridges capped by the "gravel" deposits drop steeply away into deep canyons and gorges. If the Tungsten Mountain deposits were deposited by mountain streams the only conclusion is that the topography since deposition has completely reversed itself, and what was once the floor of a canyon or valley is now the top of a peak or ridge. This implies erosion of as much as 1000 feet of rock from above the level of the deposits and as much as 1000 feet of canyon cutting below the level of the deposits. The chance that the deposits would have been preserved throughout this period of topographic reversal appears remote. The implications of this conclusion are out of harmony with the general picture of the physiographic development of the Front Range as presented by Van Tuyl and Lovering in other parts of their paper. The suggestion that the Tungsten Mountain deposits are gravels transported by a mountain stream, in the light of the above argument, cannot be accepted by the present writer.

The Tungsten Mountain deposits and their eastward extension resemble in certain respects the gravel covering terraces and pediments along the east side of the Front Range, and the possibility of a similar origin should be entertained. Rich (1935) suggested that pedimentation has been active in developing many of the surfaces referred to by Van Tuyl and Lovering as peneplains. The gradient of the surface beneath the deposits on Tungsten Mountain is a little steeper than the surface under the gravels farther east. This might be interpreted to mean that the gravels were laid down on a pediment at the edge of a slightly higher surface to the west. This sup-

position is more reasonable than the one in which the gravels are regarded as having been deposited by a mountain stream because the gravels might reasonably be interpreted as residual cappings left by deep dissection of a relatively smooth, gravel-coated pediment. The presence of quartz monzonite porphyry pebbles which, had they come from the nearest known source at Ute Mountain, must have traveled 5 miles before they reached their present resting place is a disturbing factor. Also the presence of boulders up to 15 feet in diameter is explained with difficulty. It is well known that in certain regions mud flows spreading out over relatively flat surfaces raft large boulders for considerable distances, but the Tungsten Mountain deposit contains little material that could be classified as mud or solidified mud. Moreover, the bulk of the pebbles are coarse-grained, quartzose rocks derived from the granite and gneiss of the pre-Cambrian core of the Front Range, and the postulation of mud flows of considerable lateral extent seems inadequate to explain the observed features.

For several reasons enumerated below, the present writer favors the view that the Tungsten Mountain deposit consists of glacial till. The deposit is unsorted and consists of boulders of greatest diameters approximating 15 feet embedded in a heterogeneous mixture of smaller boulders, sand, and rock flour. Soled, subrounded-to-angular boulders and pebbles are abundant. A few pebbles show grooves interpreted as striae. Screen analyses show a complete lack of sorting in the angular, finer-grained material in which the boulders are embedded. The deposits on and east of Tungsten Mountain topographically occupy positions comparable to deposits of recognized till on interstream areas in other parts of the Front Range. Ice spreading laterally over a surface of low relief could easily transport the large boulders embedded in the deposits and for distances considerably in excess of 5 miles. The only unusual feature is that the deposits lie much farther east of the crest of the mountain range than similar deposits on interstream areas elsewhere in the region. This is also true of the valley glacial deposits along North Boulder Creek near Nederland 2 miles northwest of Tungsten Mountain. Evidently this particular region was characterized by conditions which favored accumulation of unusually large amounts of glacial ice which resulted in a maximum eastward advance of the glaciers.

Northwest of Tungsten Mountain on the floor and sides of the valley of North Boulder Creek near Nederland are valley glacial deposits reaching a maximum elevation of about 8500 feet, but these deposits are related to the Tungsten Mountain deposit in the same way that the till deposits in Albion Valley and the valley of Lake Isabelle are related to the high till on Niwot Ridge. The conclusion is that the Tungsten Mountain deposit is another remnant of the till deposited by the same ice mass that deposited till on the Flattop surface near the crest of the range.

That the till rests on the remnants of the Flattop surface at an elevation of about 12,000 feet and was once continuous with the till capping Tungsten Mountain is suggested by the projection to intersection of the surfaces on which the Tungsten Mountain and the higher tills rest. The pretill surface at Tungsten Mountain is at an elevation close to 8875 feet; 4.8 miles to the east at the most easterly exposure of the till, the elevation of the surface is 8000 feet. These elevations give a west-east gradient of about 180 feet per mile. If the pretill surface is projected westward

for about 10 miles from Tungsten Mountain toward the crest of the range, it gives an elevation of about 10,700 feet in the same region as that now occupied by the till-covered remnants of the Flattop surface. As has been stated previously the Flattop remnants are found at an elevation of approximately 11,500 to 12,000 feet. The surface on which the high till rests slopes to the east at 300 to 400 feet per mile, and if this surface is projected eastward to an intersection with the Tungsten Mountain surface a single, continuous, slightly warped surface results. Thus by balancing the actual slopes of the higher and lower surfaces the discrepancy between a projected elevation of 10,700 feet and the actual elevation of 11,500 to 12,000 feet becomes of no consequence.

These observations lead to the following conclusions: (1) In early Pleistocene the higher portions of the Front Range were covered by an ice sheet which spread out laterally over a broad, relatively smooth surface. (2) The surface over which the ice moved was a surface of low relief sloping gently to the east away from the highest portion of the uplifted area. This surface may have been dissected by shallow, stream-cut valleys, but these were not deep enough or wide enough to confine and control the movement of the ice. (3) The present canyons and gorges of the Front Range have been cut below the glaciated surface during Pleistocene and subsequent to the early ice-sheet glaciation.

The surface on which the till was deposited was not a featureless plain because several monadnocks were present. The high peaks along the present crest of the Front Range rise 1000 to 2000 feet above the surface now at the 12,000-foot level and may have been nunataks standing above the surface of the ice sheet. Outlying peaks near the mountain front also stood above the general level of the plain. An excellent example is Thorodin Mountain which rises to an elevation of about 10,500 feet 6 miles southeast of Tungsten Mountain. The preglacial surface, then, might be described as a rolling plain locally interrupted by peaks rising 2000 to 2500 feet above the general level. This surface, in the writer's opinion, is the Rocky Mountain peneplain.

The till deposits in Tungsten Mountain and the ridges to the east lie in a surface which is approximately 200 to 400 feet above the general level of the present accordant summit levels. This difference of elevation suggests that dissected remnants of the original peneplain surface have been lowered somewhat by erosion subsequent to uplift. The accordance of summits and ridge tops, following this interpretation, has been maintained by more or less uniform erosional reduction of summits and ridge tops to the present level from the surface which existed prior to the ice-sheet glaciation. Pedimentation may have been active in this reduction.

The extent of the Pleistocene erosional lowering of remnants of the Rocky Mountain surface probably varies considerably from place to place in the Front Range and is largely dependent on the stream pattern in various localities. In some areas where the drainage is poor the reduction of the surface is probably of the order of a few feet. The 200 to 400 feet of lowering in the Tungsten Mountain area may be close to the maximum. The original unmodified Rocky Mountain surface probably exists only where capping detrital deposits have been a protective cover and are still present or just recently removed.

Study of the glacial deposits leads to the same conclusions as those obtained from

a study of the igneous rocks. There is, in the writer's mind, no justification for assuming the existence of more than one Cenozoic old-age surface that might be described as a peneplain. The so-called Flattop peneplain is, according to this interpretation, actually the westward, upwarped, and/or faulted continuation of

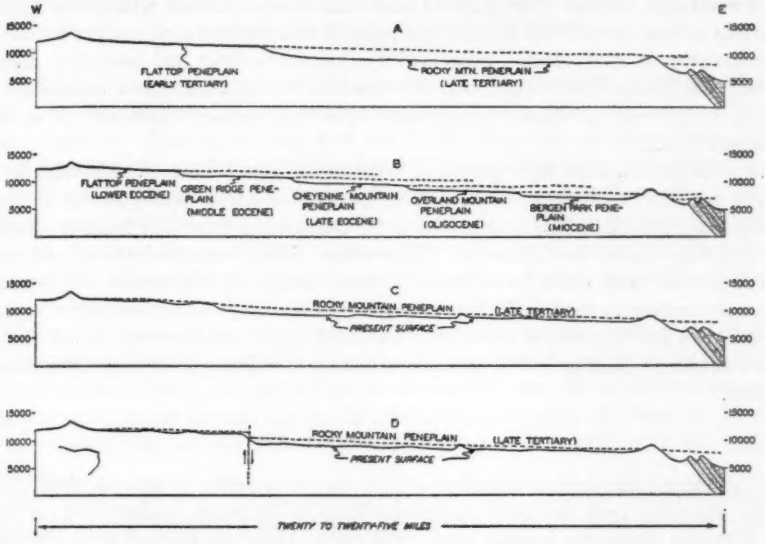


FIGURE 6.—*Comparative profiles*

A. Profile according to two-peneplain hypothesis.
B. Van Tuyl and Lovering's concept of multiple peneplains.
C, and D. Profile according to the present writer's single-surface concept.

the Rocky Mountain surface. This surface approached the characteristics of a plain some time before the Pleistocene ice-cap glaciation of the Front Range and probably reached its maximum development sometime in the late Pliocene or early Pleistocene.

The assertion that there is evidence for only one well-developed, extensive erosion surface in the Front Range is reminiscent of the conclusion reached by W. M. Davis (1911). The evidence presented above probably gives a more accurate notion of its age.

Figure 6 shows diagrammatic west-east profiles of the Front Range. Figure 6A depicts the relations that exist according to the two-peneplain hypothesis. The surfaces present according to the multiple-peneplain hypothesis of Van Tuyl and Lovering (1935) are illustrated in Figure 6B. Figure 6C and 6D portray the present writer's concept of a single differentially uplifted and dissected surface.

RATE OF CANYON CUTTING

According to the writer's interpretation the magnificent canyons and gorges of the Front Range were carved out of solid rock during the Pleistocene. Except for the higher peaks along the crest and a few isolated peaks nearer the mountain

front, the pre-Pleistocene landscape has been largely destroyed. Canyons as much as 2000 feet deep have been eroded in what to some physiographers may seem an incredibly short time. However, the belief that most of the physiographic features of the Front Range are of recent formation is not original with the present writer.

Atwood and Atwood (1938, p. 977) state that after successive widespread uplifts starting in late Tertiary the rejuvenated streams first widened their valleys and later (presumably in Pleistocene?) excavated the present valleys and canyons. Behre (1933) and Powers (1935) state that the valley of the Arkansas River including the Royal Gorge was cut below the present 12,000-foot surface subsequent to a late Pliocene uplift.

Several investigators have presented evidence to prove Pleistocene erosion on a grand scale in other areas of the United States. Matthes (1930) stated that an inner gorge 1500 feet deep was produced by Quaternary erosion of massive granite in Yosemite Valley in California. Blackwelder (1934) advanced the theory that the Colorado River carved out Grand Canyon during the Pleistocene. These two examples appear to support the present writer's contention that there was adequate time for the development of virtually all the relief features of the Front Range during the Pleistocene subsequent to, and as a result of, late Pliocene or early Pleistocene uplifts.

DIFFERENTIAL EROSION

The preice sheet surface described above was not a perfectly smooth plain. Locally, along the crest and near the present front of the range, peaks stood up 2000 to 2500 feet above the general level. The peaks along the present crest probably were erosional remnants which were aligned along the previously existing divide. Their location probably reflects the fact that the cutting power of the streams near the divide was at a minimum, and, even though the region to the east was largely base leveled, the peaks remained. There is no evidence that these crest peaks contain more resistant material than the adjacent valleys.

However, the peaks close to the present mountain front tell a different story. Almost without exception these contain resistant cores of pre-Cambrian rocks or small stocks and dikes of Tertiary igneous rocks.

Erosion below the level of the preice cap surface, the Rocky Mountain peneplain, has brought these resistant, rock-cored peaks into bolder relief. In Boulder County many peaks, such as Sugarloaf Peak, stand conspicuously above the level of the accordant summits. The elevations of most of these peaks is such that they must have stood above the original Rocky Mountain surface.

PLEISTOCENE UPLIFT OF THE FRONT RANGE

The uplift of the Front Range to its present elevation was not the result of a single upheaval. The presence of more or less poorly developed terraces in the canyons in the mountains and very well-developed terraces in the valleys east of the mountains suggests intermittent uplifts. The terraces are cut below and postdate the early Pleistocene ice-sheet till.

Along the east side of the Front Range Worcester (1931) recognized four and in some places five interrupted cycles of erosion in the valleys shown by terraces and benches along the streams. According to the present writer's interpretation all these terraces and benches are of Pleistocene or Quaternary age.

EROSION OF WARPED OR FAULTED UPLIFTED SURFACES

Lee (1923) accepted as proof of the existence of two peneplains at different levels the fact that the lower surface in plan appears to interfinger with salients of the upper surface. That is, extensions of the Rocky Mountain peneplain seem to extend back into the area of the Flattop peneplain at the elevation of the floors of the valleys cut below the Flattop level. Moreover, if the high surfaces of the Front Range are viewed from a point near the eastern edge of the range, a steplike relationship between the lower and higher surfaces appears to exist. In the writer's opinion this relationship is partly illusory and partly the result of erosion of an upwarped and/or faulted, single, originally continuous surface.

As has been pointed out, the slopes of the lower and higher portions of the uplifted surface in the Boulder area are unequal. Near the crest of the range the remnants of the socalled Flattop peneplain slope to the east at about 300 to 400 feet per mile. Farther east, in the area of the Rocky Mountain peneplain, the slope to the east is more nearly 200 feet per mile. This relationship implies warping of the uplifted surface.

The cutting power of streams flowing over the warped surface probably reached a maximum near the base of the more steeply inclined portion of the surface, because here the gradient of the stream was steep, and the volume of water greater than at the crest of the range. As the streams flowed out on the flatter portion of the surface the velocity decreased, and the cutting power was diminished. In effect the flatter portion of the surface acted as a temporary base level.

The depth of downward cutting of the streams at the change in slope was determined largely by the elevation of the flatter portion of the uplifted surface at the change in slope. Headward erosion and widening of the valley floor would result in the development of westward extensions of the flatter surface below the level of and interfingering with salients of the higher, more steeply inclined surface. Figures 7A and B show how this process operates. Figure 7C shows in plan the interfingering of salients of the two surfaces as a result of the process described above. Figure 7D shows that dissection of an erosion surface dislocated by faulting gives virtually the same result as stream erosion of an upwarped surface.

In this discussion the modifying effects of valley glaciation are ignored, but the scouring action of ice confined to the valleys would serve to intensify the process. One result of valley glaciation would be the further apparent extension of the lower surface toward the heads of the valleys.

It should not be assumed that stream erosion is the only erosional process leading to the development of the steplike surface features. As Rich (1935) pointed out, pedimentation may be very active in the Front Range. The westward extension of pedimentlike surfaces from the flatter portion of the Rocky Mountain surface

would tend to emphasize the results of normal stream erosion and would contribute to the isolation of remnants of the higher, more steeply inclined extensions of the Rocky Mountain surface.

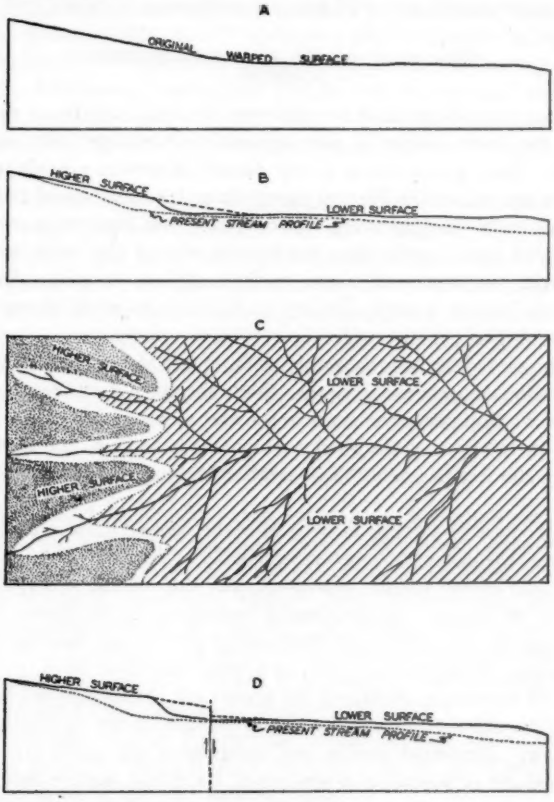


FIGURE 7.—*Development of interfingering remnants of erosion surfaces.*
Erosion is of a single differentially upwarped or faulted surface.
A. Original warped surface.
B. Surface after erosion.
C. Plan showing interfingering surfaces after erosion.
D. Profile after erosion of faulted surface.

SUMMARY OF CONCLUSIONS

Relationships between remnants of pre-Pleistocene old-age erosion surfaces, the geologic structures truncated by them, and the glacial deposits resting on them lead to the following conclusions:

(1) Dating of surfaces bevelling masses of extrusive igneous rocks indicates the existence of only one extensive old-age surface of Cenozoic age in the Front Range. This surface probably reached its maximum development in late Pliocene or early Pleistocene.

(2) Repeated mid-and late-Tertiary displacements along faulted zones militate against the supposition that accordant surfaces at high levels are remnants of an early Cenozoic peneplain.

(3) The distribution of remnantal pre-Wisconsin till deposits strongly favors the notion of a single, uplifted, warped surface. Remnants of this surface have been lowered more or less uniformly and modified by erosion postdating the pre-Wisconsin till.

(4) The present deep canyons and valleys of the Front Range were cut during Pleistocene subsequent to the deposition of pre-Wisconsin till by an ice sheet moving over a relatively flat surface.

(5) The multiple-peneplain hypothesis largely ignores the effects of differential erosion of rocks of unlike resistance.

(6) The apparent steplike relationship between the higher and lower surfaces emphasized in the two-peneplain hypothesis is explained as resulting from the erosion of a differentially upwarped and/or faulted, single, originally continuous surface. Pedimentation may have been a modifying factor.

(7) The term "Rocky Mountain peneplain" is retained, but it is applied to a late Cenozoic, probably late Pliocene or early Pleistocene old-age surface, now largely destroyed by erosion. This surface was locally interrupted by 2000-foot monadnocks.

(8) The Flattop "peneplain" of earlier writers is regarded as the lateral extension and time equivalent of the Rocky Mountain peneplain.

REFERENCES CITED

Atwood, W W., and Atwood, W. W., Jr. (1938) *Working hypothesis for the physiographic history of the Rocky Mountain region*, Geol. Soc. Am., Bull., vol. 49, p. 957–980.

Behre, C. H. Jr. (1933) *Physiographic history of the upper Arkansas and Eagle Rivers, Colo.*, Jour. Geol., vol. 41, p. 812.

Blackwelder, E. (1934) *Origin of the Colorado River*, Geol. Soc. Am., Bull., vol. 45, p. 551–565.

Davis, W. M. (1911) *The Colorado Front Range*, Assoc. Am. Geog., Ann., vol. 1, p. 21–84.

Fenneman, N. M. (1931) *Physiography of the western United States*, McGraw-Hill, New York.

Finlay, G. I. (1916) *Description of the Colorado Springs folio*, U. S. Geol. Survey, Folio no. 203.

Gazin, C. L. (1935) *A marsupial from the Florissant beds of Colorado*, Jour. Paleont., vol. 9, p. 57–62.

Lee, W. T. (1917) *The geologic story of Rocky Mountain National Park, Colorado*, Dept. Interior, Nat. Park Service.

——— (1923) *Peneplains of the Front Range and Rocky Mountain National Park, Colorado*, U. S. Geol. Survey, Bull. 730A.

Little, H. P. (1925) *Erosional cycles of the Front Range and their correlation*, Geol. Soc. Am., Bull., vol. 36, p. 495–512.

Loughlin, G. F., and Koschmann, A. H. (1935) *Geology and ore deposits of the Cripple Creek district, Colorado*, Colo. Sci. Soc., Pr., vol. 13, p. 239–241.

Lovering, T. S. (1930) *The Granby anticline, Grand County, Colorado*, U. S. Geol. Survey, Bull. 822, p. 71-76.

——— (1932) *Preliminary map showing the relation of ore deposits to geologic structure in Boulder County, Colorado*, Colo. Sci. Soc., Pr., vol. 13, p. 77–88.

Mather, K. F. (1925) *Physiographic surfaces of the Front Range of northern Colorado and their equivalents on the Great Plains*, (Abstract), Geol. Soc. Am., Bull., vol. 36, p. 134–135.

Matthes, F. E. (1930) *Geologic history of Yosemite Valley*, U. S. Geol. Survey, Prof. Paper 160, p. 118.

Powers, W. E. (1935) *Physiographic history of the upper Arkansas Valley and the Royal Gorge, Colorado*, Jour. Geol., vol. 43, p. 184–199.

Rich, J. L. (1935) *Physiographic development of the Front Range* (Discussion), Geol. Soc. Am., Bull., vol. 46, p. 2046–2051.

Spock, L. E. Jr. (1928) *Reconnaissance of parts of Grand, Jackson, and Larimer Counties, Colorado*, N. Y. Acad. Sci., Ann., vol. 30, p. 177–261.

Stark, J. T., Johnson, J. H., Behre, C. H., Jr., Powers, W. E., Howland, A. L., and Gould, D. B. (1935) *History of South Park, Colorado* (Abstract), Geol. Soc. Am., Pr. 1934, p. 107.

Van Tuyl, F. M., and Lovering, T. S. (1935) *Physiographic development of the Front Range*, Geol. Soc. Am., Bull., vol. 46, p. 1291–1350.

Wahlstrom, Ernest E. (1944) *Structure and petrology of Specimen Mountain, Colorado*, Geol. Soc. Am., Bull., vol. 55, p. 77–90.

Wegemann, C. H. (1944) *A guide to the geology of Rocky Mountain National Park*, U. S. Dept. Interior, Nat. Park Service.

Wilmarth, M. G. (1938) *Lexicon of the geologic names of the United States*, U. S. Geol. Survey, Bull. 896, pt. 2, p. 1514.

Worcester, P. G. (1931) *Peneplanation and base-leveling in the Rocky Mountains* (Abstract), Jour. Colo.-Wyo. Acad. Sci., vol. 1, p. 27–28.

——— (1939) *Textbook of geomorphology*, D. Van Nostrand Co., New York, p. 540–551.

University of Colorado, Boulder, Colorado.

Manuscript Received by the Secretary of the Society, April 25, 1945.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 58, PP. 573-598, 1 FIG. JULY 1947

CHEMICAL ANALYSES AND CALCULATED MODES OF THE OLIVERIAN MAGMA SERIES, MT. WASHINGTON QUADRANGLE, NEW HAMPSHIRE

(Shaler Memorial Series)

BY MARLAND P. BILLINGS AND JOHN C. RABBITT

CONTENTS

	Page
Abstract	574
Introduction	574
Modes	574
Chemical analyses	575
General statement	575
Regular analyses	576
Spectrographic analyses	579
Significance of spectrographic analyses	579
Calculated modes	582
General statement	582
Method	582
Introduction	582
Muscovite, chlorite, sphene	584
Zircon	585
Sulfide	585
Apatite	585
Calcite	586
Magnetite, ilmenite, biotite, and hornblende	586
Feldspar, clay minerals, and sericite	588
Quartz	590
Totals	590
Errors and limits of accuracy	590
General statement	590
Size of sample	590
Accuracy of analyses	591
Incompleteness of regular analyses	591
Use of molecular proportions	591
Use of theoretical minerals	592
Accuracy of Rosiwal analyses	593
Accuracy of determining anorthite content of plagioclase	593
Summary of errors	594
Test of accuracy	594
Summary	595
References cited	595

ILLUSTRATIONS

Figure	Page
1. Variation diagram, Oliverian magma series, Mt. Washington quadrangle, New Hampshire	578

ABSTRACT

Complete chemical analyses, including the spectrographic determination of 44 trace elements, have been made of six representative specimens from each of the six map units constituting the Oliverian magma series in the Mt. Washington quadrangle of New Hampshire. Potash is systematically higher than soda. An increase in silica, which ranges from 56 to 75 per cent, is accompanied by the usual variation of the other principal oxides; lime, magnesia, and total iron decrease in the more siliceous rocks, whereas potash and soda increase at first and then decline. Potash is 1.5 to 3 per cent higher than soda throughout the series.

With increasing silica content Cr_2O_3, NiO, SrO, V_2O_5, and BaO decrease, but ZnO increases. Comparisons with other parts of the world, especially northwestern Europe, suggest some systematic differences from New Hampshire, but the data are insufficient to justify any definite conclusions.

The calculation of modes from the chemical analyses necessitates a discussion of the methods involved and the possible errors. It is believed that in these rocks the modes can be calculated with relatively small errors. An unexplained excess of alumina in the modes, ranging from 0.0 to 1.0 per cent, may be due to more sericite and clay minerals in the rocks than the content of water suggests.

INTRODUCTION

The igneous rocks of the Oliverian magma series in the Mt. Washington quadrangle of New Hampshire have been described by C. A. Chapman, M. P. Billings, and R. W. Chapman (1944). Detailed petrographic descriptions, including modes, were given in that paper, but chemical analyses were not available because the Rock Analysis Laboratory at the University of Minnesota was closed due to the war. In 1945 and 1946, however, the necessary analyses, financed by a grant from the Shaler Memorial Fund of Harvard University, were made by Mr. Lee C. Peck of the Rock Analysis Laboratory. It was also possible to make detailed spectroscopic analyses in the Department of Mineralogy and Petrography of Harvard University, using the same powders as those that Mr. Peck had analyzed. This spectrographic work, directed by Prof. E. S. Larsen, Jr., has been financed in part by grants from the Associates in Science of Harvard University. Professor Larsen's program to study trace elements, initiated in 1939, was unfortunately interrupted during the war years. The writers are greatly indebted to him for this opportunity to present some of the first results of his program. Mr. Rabbitt made the spectrographic analyses, and Mr. Billings is responsible for the rest of the paper.

MODES

The rocks of the Oliverian magma series in the Mt. Washington quadrangle have been assigned to six map units: (1) hornblende-quartz monzonite, (2) fine-grained gray quartz monzonite, (3) coarse syenite, (4) coarse granite, (5) biotite-quartz monzonite, and (6) porphyritic biotite-quartz monzonite. Average modes, in weights per cent, are given in Table 1. They have been recalculated from the volumes per cent given in Table 1 of the paper by C. A. Chapman, M. P. Billings, and R. W. Chapman (1944), in which the range in mineral composition of each of the six types was also tabulated.

Most of these modes are believed to have consolidated from magma, but some of

the hornblende-quartz monzonite may be the product of metasomatic replacement of metamorphosed volcanic rocks (Chapman, Billings, and Chapman, 1944, p. 511–512).

TABLE 1.—*Average modes in weight per cent of the Oliverian magma series, Mt. Washington quadrangle, New Hampshire*

	(1)	(2)	(3)	(4)	(5)	(6)
Quartz	14	27	6	33	33	31
Potash-soda feldspar	35	23	57	41	32	32
Plagioclase	30	35	29	20	29	27
Biotite	5	11	2	2	4	6
Hornblende	15	0	5	1	0	0
Muscovite	0	2	0	0	1	2
Opaques	tr	2	1	2	1	1
Sphene	1	0	tr	1	tr	tr
Apatite	tr	tr	tr	tr	tr	tr
Zircon	tr	tr	tr	tr	tr	tr
Chlorite	tr	tr	tr	tr	tr	1
Allanite	tr	tr	tr	tr	tr	0
Epidote	tr	tr	tr	tr	tr	tr
Pyroxene	0	0	tr	tr	0	0
Rutile	tr	tr	tr	0	tr	0
Garnet	0	0	0	0	tr	0
Tourmaline	0	0	tr	0	0	0
Andalusite	0	0	0	0	0	tr
Sillimanite	0	0	0	0	0	tr
Per cent of anorthite in plagioclase	38	22	21	18	17	17

1. Hornblende-quartz monzonite, average of 6 thin sections.
2. Fine-grained gray quartz monzonite, average of 4 thin sections.
3. Coarse syenite, average of 11 thin sections.
4. Coarse granite, average of 6 thin sections.
5. Biotite-quartz monzonite, average of 10 thin sections.
6. Porphyritic biotite-quartz monzonite, average of 8 thin sections.

CHEMICAL ANALYSES

GENERAL STATEMENT

Six chemical analyses, one for each of the principal map units found in the Oliverian magma series of the Mt. Washington quadrangle, are given in Tables 2 and 3. The regular chemical analyses are given in Table 2, and the spectrographic data are presented in Table 3. In general, the analyses were made on specimens which, judging from thin-section study, seemed to represent the average of each type. As will be shown later, this objective was generally achieved. However, the coarse syenite and the hornblende-quartz monzonite are largely confined to the northern part of the Mt. Washington quadrangle in the area mapped by the Chapmans. They were both overseas at the time the specimens were sent for analysis, and their collections were not accessible. No specimen of coarse syenite suitable for analysis was available

in Billings' collection, but in the spring of 1945 R. F. Story kindly obtained several specimens from this map unit. The most satisfactory specimen, somewhat weathered, was sent for analysis. The specimen of hornblende-quartz monzonite chosen

TABLE 2.—*Chemical analyses, Oliverian magma series, Mt. Washington Quadrangle, New Hampshire*

	(1)	(2)	(3)	(4)	(5)	(6)
SiO_2	55.83	69.83	60.59	74.19	75.08	73.73
TiO_2	0.90	0.48	0.52	0.20	0.20	0.24
Al_2O_3	17.11	15.53	18.74	14.13	13.75	13.95
Fe_2O_3	1.82	0.76	2.05	0.72	0.37	0.38
FeO	3.86	1.96	1.45	0.65	1.05	1.55
MnO	0.13	0.08	0.09	0.03	0.05	0.06
MgO	3.78	0.74	1.06	0.33	0.32	0.45
CaO	5.78	1.80	2.61	1.09	0.98	1.01
Na_2O	2.86	3.41	4.50	3.29	3.19	3.20
K_2O	6.17	4.83	7.19	5.26	4.83	4.86
H_2O+	0.89	0.46	0.55	0.27	0.25	0.32
H_2O-	0.04	0.03	0.05	0.04	0.04	0.08
P_2O_5	0.62	0.25	0.28	0.04	0.04	0.07
CO_2	n.d.	n.d.	0.40	n.d.	n.d.	n.d.
Cl	0.02	0.02	0.04	0.01	0.01	0.01
F	0.13	0.12	0.05	0.04	0.03	0.03
S	0.00	tr	0.00	0.04	0.01	0.01
Total.....	99.94	100.30	100.17	100.33	100.20	99.95
Less O.....	0.05	0.05	0.03	0.03	0.02	0.02
Total.....	99.89	100.25	100.14	100.30	100.18	99.93

1. Hornblende monzonite facies of the hornblende-quartz monzonite, Spec. W-206; altitude of 1260 feet, just below dam, Stag Hollow Brook, Jefferson Highlands, Mt. Washington quadrangle, N. H. Lee C. Peck, analyst, 1945.

2. Fine-grained gray quartz monzonite, Spec. W-F6; Moose River, 0.4 mile northeast of Bowman Station, Randolph township, Mt. Washington quadrangle, N. H. Lee C. Peck, analyst, 1945.

3. Coarse syenite, Spec. W-R 21; 0.5 mile east of B.M. 1195, which is 2 miles north-northwest of village of Jefferson, Mt. Washington quadrangle, N. H. Lee C. Peck, analyst, 1945.

4. Coarse granite, Spec. MW-122; U. S. Highway No. 2, 2 miles west of Bowman, 0.15 mile east of Randolph-Jefferson town line, Mt. Washington quadrangle, N. H. Lee C. Peck, analyst, 1945.

5. Biotite-quartz monzonite, Spec. MW-120; U. S. Highway No. 2, 0.3 mile west of Ravine House, Randolph, Mt. Washington quadrangle, N. H. Lee C. Peck, analyst, 1945.

6. Porphyritic biotite-quartz monzonite, Spec. MW-L 28; altitude of 2400 feet on trail leading northwest from Pine Peak (erroneously called Pine Mtn. on topographic map), Low and Burbanks Grant, Mt. Washington quadrangle, N. H. Lee C. Peck, analyst, 1945.

for analysis was not representative of this unit, as it was richer in hornblende and potash feldspar but poorer in quartz than the average for this rock.

The specimens were crushed at the Rock Analysis Laboratory of the University of Minnesota. Prof. F. F. Grout kindly supplied Rabbit with samples of these powders for the spectrographic studies.

REGULAR ANALYSES

The regular chemical analyses, made by Lee C. Peck of the Rock Analysis Laboratory of the University of Minnesota, are given in Table 2. The six columns represent

the same columns as given in Tables 1 and 6. Columns 2, 4, 5, and 6 are respectively representative of the fine-grained gray quartz monzonite, coarse granite, biotite-quartz monzonite, and porphyritic biotite-quartz monzonite. Column 3, except for the fact that the rock it represents is somewhat weathered, is representative of

TABLE 3.—*Spectrographic analyses of the Oliverian magma series, Mt. Washington Quadrangle, New Hampshire*

	(1)	(2)	(3)	(4)	(5)	(6)
B_2O_3	0.001	0.001	*	*	0.001	*
BaO	0.3	0.1	0.2	0.1	0.2	0.2
Co_2O_3	*	*	*	*	0.001	*
Cr_2O_3	0.01	0.004	0.005	0.002	0.002	0.001
Cs_2O	*	*	0.001	0.001	0.001	*
CuO	0.005	0.003	0.001	0.001	0.006	0.001
Li_2O	0.07	0.07	0.003	0.07	0.08	0.08
MnO_2	0.05	0.05	0.05	0.02	0.04	0.03
NiO	0.006	0.005	0.004	*	0.001	*
PbO	0.005	0.003	0.005	0.004	0.005	0.004
Sc_2O_3	0.003	0.003	0.002	0.002	0.003	0.002
SnO	0.001	*	*	*	0.001	*
SrO	0.4	0.08	0.2	0.07	0.06	0.03
V_2O_5	0.03	0.02	0.03	0.005	0.006	0.006
ZnO	*	0.001	*	0.002	0.001	0.001
ZrO_2	0.02	0.01	0.04	0.01	0.01	0.008

* Tested for, but if present, are in quantities less than 0.001%.

The following were tested for in all six specimens but, if present, are in quantities less than 0.001%: As_2O_3, BeO, Bi_2O_3, CdO, HgO, MoO_3, Sb_2O_3, Rb_2O, Ag_2O, Au, In_2O_3, GeO_2, Cb_2O_5, Ta_2O_5, Pd, Pt, Os, Ir, CeO_2, Ga_2O_3, La_2O_3, Rh, Ru, Te, Yb, and Y.

WO_3, if present is less than 0.01% in each of the six specimens.

Re, if present, is less than 0.002% in each of the six specimens.

1. Hornblende monzonite facies of hornblende-quartz monzonite.
2. Fine-grained gray quartz monzonite.
3. Coarse syenite.
4. Coarse granite.
5. Biotite-quartz monzonite.
6. Porphyritic biotite-quartz monzonite.

The same powders were used as for the regular analyses.

Analyst, John C. Rabbitt, 1946.

the coarse syenite. Column 1, as shown by the calculated mode in Table 6, technically represents a hornblende monzonite near the border line with syenite, as the quartz is less than 5 per cent and potash-soda feldspar is 66 per cent of the total feldspar.[1]

In most respects the analyses are not unusual. The coarse syenite is unusually rich in alkalies, especially potash. The hornblende monzonite facies of the hornblende-quartz monzonite is also unusually rich in potash, particularly in view of the

[1] In general, Johannsen's scheme of classification is used in New Hampshire, although his terminology is modified somewhat. In syenite and granite the potash-soda feldspar constitutes more than 67 per cent of the total feldspar; in monzonite and quartz monzonite the potash-soda feldspar ranges from 67 per cent to 33 per cent of the total feldspar; in monzodiorite and granodiorite the potash-soda feldspar ranges from 33 per cent to 5 per cent of the total feldspar; and in diorite and quartz diorite the potash-soda feldspar is less than 5 per cent of the total feldspar. Potash-soda feldspar includes orthoclase, microcline, and perthite.

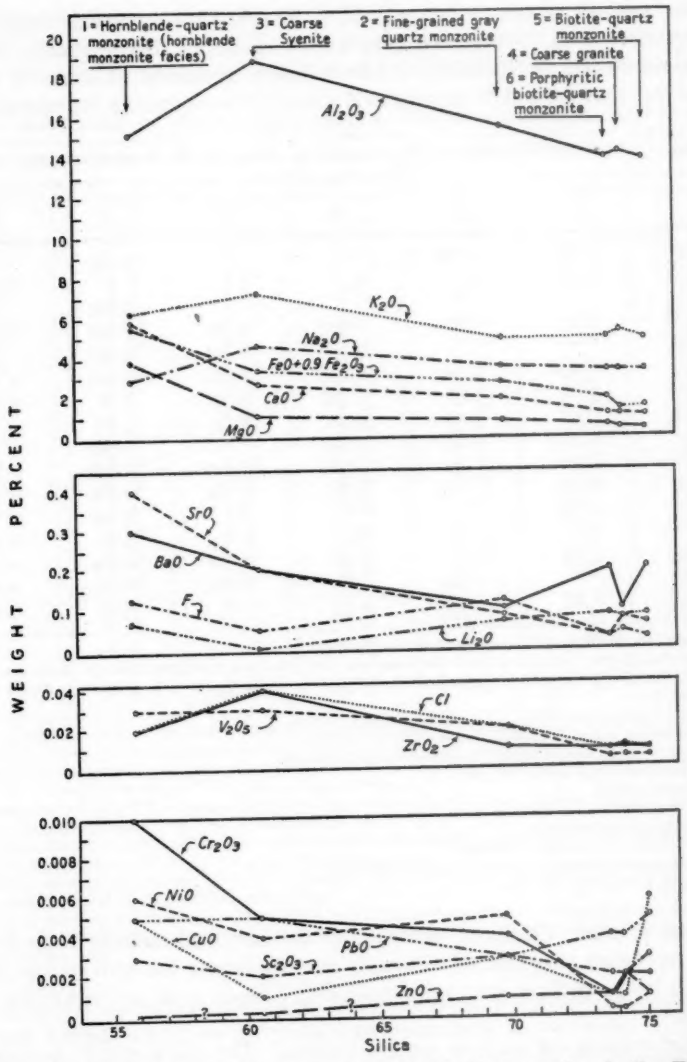


FIGURE 1.—*Variation diagram, Oliverian magma series, Mt. Washington quadrangle, New Hampshire*

large content of lime. The biotite-quartz monzonite and the prophyritic biotite-quartz monzonite are very similar to each other. Apparently the phenocrysts of potash-soda feldspar in the latter do not cause an increase in the content of alkalies in the rock.

The principal oxides listed in the regular analyses have been incorporated into the uppermost part of the variation diagram shown in Figure 1. They show the

expected variations. With increasing SiO_2 there is a decrease in MgO, CaO, and total iron. Na_2O, K_2O, and AlO_3 reach a maximum value in the syenite, in which SiO_2 is close to 60 per cent. K_2O is 1.5 to 3 per cent higher than soda throughout the diagram. But a high K_2O/Na_2O ratio is not everywhere characteristic of the Oliverian magma series, and Hadley (1942, p. 140) has given analyses in which soda is distinctly dominant over potash.

SPECTROGRAPHIC ANALYSES

For each sample, 5 grams of the same powder used for the regular chemical analysis were ground for 10 minutes in an agate mortar. Five hundred milligrams of this powder were weighed 50/50 with graphite powder ground from National Carbon Company Special graphite electrodes. This mixture was mixed thoroughly and ground in an agate mortar to minus 400-mesh, and 30 milligrams of this material were subsequently burned in the arc.

The spectrograph used consisted of a 4-inch, 15,000-line/inch concave reflecting grating of 2-meter radius in a Baird Associates modified Eagle mounting. The spectrograms were recorded on 4 by 10-inch Eastman spectrographic plates, types II-O, I-F, and I-N. These plates were developed by the time-temperature method for 3 minutes at 68°C. in Eastman D-19 developer.

Thirty milligrams of each sample were burned in a DC arc operating at 13 amperes. National Carbon Co. Special graphite electrodes were used, the one containing the sample being the positive electrode. The shutter was opened before the arc was struck, and the sample was then burned to completion, the average exposure time being about 2 minutes. Duplicates of all samples were run, as were blanks of the electrodes and samples of all materials used in the standards. Standards were run on the same plates as those of the rock samples. These standards consisted of appropriate amounts of the different elements in a base consisting of SiO_2, Al_2O_3, CaO, MgO, K_2O, and Na_2O.

Quantitative estimations were made by visual examination of the plates, second-order lines being used. The results are thought to be accurate within ± 15 per cent of the amounts present.

The results of the spectrographic analyses are presented in Table 3. In the main part of the table the amounts are given in weight per cent, just as in the regular analyses. A figure of 0.0001 would be equivalent to one part per million. Those elements that gave negative results in all six specimens are listed in the lower part of the table. This does not mean that these elements are not present; it merely indicates that they are present in amounts less than the sensitivity of the method. Although most elements can be determined quantitatively if they are present in amounts equal to or greater than 0.001 weight per cent, this is not always the case. WO_3, for example, can be determined spectrographically only if it makes up at least 0.01 per cent of the specimen.

SIGNIFICANCE OF SPECTROGRAPHIC ANALYSES

The regular analyses in Table 2 are incomplete, and spectrographic data in Table 3 show that the chemistry of the rocks is actually different from the figures given in

Table 2. According to F. A. Gonyer, who kindly discussed this subject with the authors, the oxides not listed in Table 2 fall into several categories. In the first group are those that are not precipitated with any other element and do not appear in the regular analyses; the totals in Table 2 are thus deficient to the same amount as these oxides appear in Table 3. The most important oxide in this group is BaO, but CuO and ZnO are also of this type. In a second group are those oxides that are precipitated with some other oxide and thus give too high a value for some of the figures in the regular analyses. The most important of these is SrO, which appears as CaO in the regular analysis; that is, the actual amount of CaO in the rocks is not the amount given in Table 2 but is this amount less the amount of SrO given in Table 3. Li_2O would probably appear as Na_2O. Cs_2O would be precipitated with K_2O. Still other oxides would probably appear as Al_2O_3 in Table 2; among these are SnO, ZrO_2, PbO, and Sc_2O_3. The behavior of some oxides is too involved to discuss here, but the following might appear in part as Al_2O_3 in Table 2: Cr_2O_3, Co_2O_3, NiO, V_2O_5, and B_2O_3. The totals, however, of these oxides that might appear as Al_2O_3 are relatively small, ranging from a minimum of 0.021 weight per cent to a maximum of 0.086. It is apparent that the excess Al_2O_3 that is discussed on a later page cannot be accounted for in this way.

A "corrected" series of analyses could be presented, in which the figures appearing in Table 2 are adjusted in accordance with the data given in Table 3. This would be rather hazardous without the additional check of chemical methods. The correction would be quantitatively important for only three oxides: BaO should be listed in the analysis; SrO should be listed, and CaO reduced by a corresponding amount; and Li_2O should be listed, and Na_2O probably reduced by a corresponding amount.

The manner in which the quantity of each trace element changes with silica content is shown in the variation diagram (Fig. 1). Whereas the uppermost part of this diagram is for the common oxides, the rest of the diagram is for those elements occurring in amounts less than 0.5 per cent. From the diagram it is apparent that the following trace elements decrease with increasing silica: Cr_2O_3, NiO, SrO, V_2O_5, and BaO. ZnO seems to increase with increasing SiO_2. The following show no significant change: PbO, CuO, Sc_2O_3, Li_2O, Cl, F, and ZrO_2.

Because of the small number of analyses, it would be exceedingly hazardous to make any generalizations from these observations. Moreover, the least siliceous rock analyzed contains nearly 56 per cent SiO_2, and less siliceous rocks have not been studied in this investigation. Many spectrographic analyses of the different minerals in the rocks would be necessary to determine the manner in which the trace elements are distributed within the rocks.

The maximum possible amount of some of the accessory minerals may be calculated from the figures in Table 3. For example, even if all the B_2O_3 were confined to tourmaline, this mineral could not exceed 0.01 per cent of any of the rocks. If all the CeO_2 were confined to allanite, this mineral could not exceed 0.005 per cent of any of the rocks.

Data have been assembled in Table 4 to compare the amounts of the trace elements in the Oliverian magma series with the quantities in similar rocks elsewhere. Although Bray (1942) and Shimer (1943) have published data concerning the trace

elements in minerals and rocks in the United States, they give only qualitative data for rocks, and a comparison with the figures presented here is not possible. Column 1 of Table 4 gives average figures for the most siliceous members of the Oliverian

TABLE 4.—*Quantities of trace-elements compared with other areas*

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
B_2O_3	0.0005	0.0005	0.0006	0.0003	0.001	0.001	0.003	*
BaO	0.15	0.25	0.110	0.07	0.05	0.05	0.1	*
BeO_2	<0.001	<0.001	0.0014	0.0003	0.0003	0.0003	0.0006	*
Co_2O_3	<0.001	<0.001	0.00001	0	0.001	0.001	0.001	0.0004
Cr_2O_3	0.002	0.007	0.0074	0.0003	0.001	0.0003	0.03	*
Cs_2O	0.0005	0.0005	0.0008	*	*	*	*	*
CuO	0.003	0.003	*	*	*	*	*	0.0026
Ga_2O_3	<0.001	<0.001	0.008	0.01	0.01	0.01	0.01	*
GeO_2	<0.001	<0.001	0.0001	*	*	*	*	*
La_2O_3	<0.001	<0.001	0.005	0.008	0.006	0.003	0.006	*
Li_2O	0.075	0.036	0.018	0.01	0.015	0.01	0.006	*
MoO_3	<0.001	<0.001	*	*	*	*	*	0.00038
NiO	0.002	0.005	0.0004	0.0003	0.001	0.0003	0.001	0.00074
PbO	0.004	0.005	0.001	0.003	0.001	0	<0.001	0.0021
Rb_2O	<0.001	<0.001	0.12	0.1	0.08	0.05	0.05	*
Sc_2O_3	0.0025	0.0025	0.001	0.0001	0.0001	0.0001	0.0003	*
SrO	0.06	0.3	0.017	0.01	0.01	0.01	0.08	*
Ta_2O_5	<0.001	<0.001	0.0005	*	*	*	*	*
V_2O_5	0.009	0.03	0.006	0.003	0.003	0.003	0.006	*
Y_2O_3	<0.001	<0.001	0.004	0.001	0.0003	0.001	0.001	*
ZnO	0.001	<0.001	*	*	*	*	*	0.0079
ZrO_2	0.01	0.03	0.054	0.03	0.01	0.03	0.035	*

* Indicates that element was not determined.

1. Average of coarse granite, biotite-quartz monzonite, porphyritic biotite-quartz monzonite, and fine-grained gray quartz monzonite, Oliverian magma series, Mt. Washington quadrangle, N. H.

2. Average of coarse syenite and hornblende monzonite facies of hornblende-quartz monzonite, Oliverian magma series, Mt. Washington quadrangle, N. H.

3. Averages for granites and related rocks from data given by Rankama for whole world, but mostly Europe (Rankama, 1946).

4. Averages for younger granites of southern Lapland, from Sahama (1945).

5. Averages for Hetta type of granite of southern Lapland, from Sahama (1945).

6. Averages for gneissic granite and granitic gneiss, southern Lapland, from Sahama (1945).

7. Averages for syenite series of western Lapland, from Sahama (1945).

8. Average for 29 silicic rocks from United States, Sandell and Goldich (1943, p. 182); recalculated to oxides from original data for purpose of comparison.

magma series (coarse granite, biotite-quartz monzonite, porphyritic biotite-quartz monzonite, and fine-grained gray quartz monzonite); column 2 gives average figures for the syenitic members (coarse syenite and hornblende monzonite facies of the hornblende-quartz monzonite). In column 3 are averages, prepared by Billings from data given by Rankama (1946), for rocks from all over the world, but chiefly from Europe. Columns 4 to 7 have been copied from Table XXVII in a recent paper by Sahama (1945) discussing the trace elements found in rocks from southern Finnish Lapland. Column 8 lists data obtained by Sandell and Goldich (1943) on American rocks by nonspectrographic chemical "trace" methods; their data, given as metals, have been recalculated to oxides in order to facilitate comparisons.

Some of the trace elements seem to be more abundant in the Oliverian magma series than in similar rocks elsewhere. This is notably true of SrO, which is 6 times as abundant in the granitic members of the Oliverian magma series as in similar rocks elsewhere and is 4 times as abundant in the syneitic members of the Oliverian magma series as in similar rocks in southern Finnish Lappland. Sc_2O_3 is 3 to 25 times as abundant in the New Hampshire rocks as it is elsewhere. BaO, although not significantly more abundant in the granitic rocks of the Oliverian magma series than it is in the world average, is 2 to 3 times as abundant as in comparable rocks in southern Finnish Lapland. Li_2O is 3 to 6 times as abundant in the Oliverian magma series as elsewhere. NiO is 2 to 8 times, and PbO 2 to 5 times as abundant as in the other areas represented in Table 4. V_2O_3 is 2 to 5 times as common in the New Hampshire rocks as elsewhere.

Some trace elements appear to be less abundant in the Oliverian magma series than in comparable rocks elsewhere; this is notably true of Ga_2O_3, La_2O_3, Rb_2O,and ZnO.

These conclusions must be considered distinctly tentative, because they are based on a relatively small number of analyses, particularly for New Hampshire.

CALCULATED MODES

GENERAL STATEMENT

Modes calculated from the six chemical analyses are given in Table 6. Billings has been accustomed to calculate modes from chemical analyses by a method that is essentially the one used in calculating norms, except that the computations, insofar as possible, are made in terms of actual rather than normative minerals. The method is briefly described by Kemp and Grout (1940, p. 260–263) who warn, however, that "the method should be used only with caution". Holmes (1921, p. 396–410) has also discussed the method and has emphasized the difficulties. In view of the somewhat pessimistic attitude of these authors, some discussion of the method used in the present study seems desirable. The possible errors and limits of accuracy are considered in a later section of the paper. As a specific example the calculation of the mode of the biotite-quartz monzonite, analysis No. 5, is presented in Table 5.

At the outset it should be pointed out that a more precise check on the accuracy of the calculations would have been possible if Rosiwal analyses of very large thin sections had been made and if the opaque minerals had been studied in polished sections. In all but two cases, however, the entire specimen was used for the usual thin sections and chemical analyses, and none was available for these supplementary but important investigations.

METHOD

Introduction.—Although much of the calculation can be automatic, as in the case of the norm, the amounts of a few of the minor minerals must be determined by Rosiwal analysis. This is because some oxides appear in so many minerals that it is impossible to establish equations to determine the quantity of all the minerals. The quantities of sphene, chlorite, and muscovite were determined by Rosiwal analysis. If both biotite and hornblende are present (there is no olivine and very little pyroxene in

(Spec. MW-120, biotite-quartz monzonite)

(Spec. MW-120, biotite-quartz monzonite)

(1)	(2) Weight per cent	(3) Molecular number	(4) Muscovite (1.4)*	(5) Zircon	(6) Pyrite	(7) Apatite	(8) Magnetite	(9) Ilmenite	(10) Biotite	(11) Plagioclase (An = 17) An	(11) Plagioclase (An = 17) Ab	(12) Potash-soda feldspar Cn	(12) Potash-soda feldspar Ab	(12) Potash-soda feldspar Or	(13) Sericite	(14) Kaolin	(15) Excess Al_2O_3	(16) Quartz
SiO_2	75.08	1.251	.012	n	.....	.....	.....	.....	.015	.034	.252	.002	.060	.276	.006	.004	.....	.590
TiO_2	0.20	.003	.....	.....	.....	.....	.....	.002	.001	.....	.....	.....	.....	.....	.....	.....	.....	.....
Al_2O_3	13.75	.134	.006	.....	.....	.....	.....	.....	.004	.017	.042	.001	.010	.046	.003	.002	.003	.....
Fe_2O_3	0.37	.003	.....	.....	.....	.....	.001	.....	.002	.....	.....	.....	.....	.....	.....	.....	.....	.....
FeO	1.05	}	.....	.....	n (0.01)	.....	.001	.002	.012	.....	.....	.....	.....	.....	.....	.....	.....	.....
MnO	0.05	.015	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
MgO	0.32	.008	.....	.....	.....	.....	.....	.....	.008	.....	.....	.....	.....	.....	.....	.....	.....	.....
CaO	0.98	.018	.....	.....	.....	.001 (0.05)	.....	.....	.....	.017	.....	.....	.....	.....	.....	.....	.....	.....
Na_2O	3.19	.052	.....	.....	.....	.....	.....	.....	.....	.....	.042	.....	.010	.....	.....	.....	.....	.....
K_2O	4.83	.051	.002	.....	.....	.....	.....	.....	.002	.....	.....	.....	.....	.046	.001	.....	.....	.....
P_2O_5	0.04	.....	.....	.....	.....	n (0.04)	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
H_2O+	0.25	.014	.004	.....	.....	.....	.....	.....	.005	.....	.....	.....	.....	.....	.002	.004	.....	.....
Cl	0.01	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
F	0.03	.001	.....	.....	.....	n (0.004)	.....	.....	.001	.....	.....	.....	.....	.....	.....	.....	.....	.....
S	0.01	.....	.....	.....	n (0.01)	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
BaO	0.2	.001	.....	.....	.....	.....	.....	.....	.....	.....	.....	.001	.....	.....	.....	.....	.....	.....
ZrO_2	0.01		.....	n	(0.01)	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Weights per cent of oxides assigned to mineral			.002	†	0.01	0.05	†	†	0.90	†	†	†	†	†	001	.002	.....	.590
			×796	>	0.01	0.04	.....	.....	0.08	.....	.....	.....	.....	.....	×796	×258	.....	×60
			.....	.....	.....	.....	.....	.....	0.40	.....	.....	.....	.....	.....	.....	.....	.....	.....
			=1.59	.....	.....	.....	.....	.....	0.32	.....	.....	.....	.....	.....	.80	.516	.....	35.40
			.....	.....	.....	.....	.....	.....	0.86	.....	.....	.....	.....	.....	.....	.....	.....	.....
			.....	.....	.....	.....	.....	.....	0.32	.....	.....	.....	.....	.....	.....	.....	.....	.....
			.....	.....	.....	.....	.....	.....	0.19	.....	.....	.....	.....	.....	.....	.....	.....	.....
			.....	.....	.....	.....	.....	.....	0.09	.....	.....	.....	.....	.....	.....	.....	.....	.....
			.....	.....	.....	.....	.....	.....	0.03	.....	.....	.....	.....	.....	.....	.....	.....	.....
Totals in weight per cent....			1.59	0.01	0.02	0.09	0.23	0.30	3.19	4.73	22.01	0.37	5.24	25.58	0.80	0.52	0.30	35.40
										26.74 An_{17}	Ab_{73}	31.19 Cn_2	Ab_{18}	Or_{80}	Total = 100.32			

n Indicates that molecular number is less than 0.001; number in parenthesis is weight per cent.
* Amount determined by Rosiwal analysis.
† Weight per cent obtained from Washington's tables

these rocks) the amount of the lesser one is determined by the Rosiwal method. The amount of plagioclase present as perthitic lamellae in the potash-soda feldspar is also measured. Inasmuch as these various minerals are first determined in volume per cent, the figures must be converted into weight per cent by the usual methods; that is, a complete Rosiwal analysis of the thin section is necessary.

TABLE 6.—*Modes in weight per cent calculated from chemical analyses*

		(1)	(2)	(3)	(4)	(5)	(6)
Quartz		1.2	27.7	1.7	32.0	35.3	34.1
Potash-soda feldspar		43.5	27.3	60.1	39.5	31.1	32.7
Plagioclase		22.6	32.6	23.4	23.1	26.6	24.8
Biotite		6.3	6.7	3.0	2.2	3.2	5.2
Hornblende		22.6	.....	4.3	.....	.....	.....
Muscovite		.....	2.3	.....	.....	1.6	0.8
Sulfide		.....	tr	.....	0.1	0.02	tr
Magnetite		0.9	0.5	2.0	0.7	0.2	0.3
Ilmenite		.....	0.6	.....	.....	0.3	0.1
Sphene		1.0	.....	1.3	0.4	.....	.....
Apatite		1.4	0.6	0.6	0.1	0.1	0.2
Zircon		0.03	0.01	0.06	0.01	0.01	0.01
Chlorite		.....	1.0	.....	0.5	.....	0.8
Calcite		.....	.....	0.9	.....	.....	.....
Sericite		.....	.....	.....	.....	0.8	.....
Kaolin		0.5	.....	2.0	0.8	0.5	.....
Excess Al_2O_3		.....	0.7	0.6	0.6	0.3	1.0
Composition of	Ab...	67	78	86	82	83	83
plagioclase	An...	33	22	14	18	17	17
Composition of	Cn...	3	2	1	1	2	1
potash-soda	Ab...	22	15	28	19	18	22
feldspar,*	Or...	75	83	71	80	80	77

* In the case of perthite this refers to the host only, and excludes the plagioclase lamellae in the perthite.

1. Hornblende monzonite facies of hornblende-quartz monzonite.
2. Fine-grained gray quartz monzonite.
3. Coarse syenite.
4. Coarse granite.
5. Biotite-quartz monzonite.
6. Porphyritic biotite-quartz monzonite.

As shown in Table 5, the weight per cent of each oxide as given in the regular analysis (Table 2) is listed in the second column. BaO and ZrO_2 have been added from the spectrographic analyses given in Table 3. The molecular proportions are then listed in column 3, using the Tables given in the back of Johannsen (vol. I, 1931) or Washington (1917).

Muscovite, chlorite, sphene.—Oxides are then alloted to form the right amount of those minerals, such as muscovite, sphene, and chlorite, that have been determined by the Rosiwal method. The oxides are assigned in the appropriate ratios. The allotments for muscovite are: for each 0.001 molecular proportion of K_2O one allots 0.002 molecular proportion of H_2O, 0.003 of Al_2O_3, and 0.006 of SiO_2; to determine the amount of muscovite the molecular proportion of K_2O allotted to this mineral is

multiplied by 796; for each 0.001 molecular proportion of K_2O that is used one obtains 0.80 weight per cent of muscovite. For sphene, equal molecular proportions of CaO, TiO, and SiO_2 are allotted; Washington's tables are used to determine the weight per cent of sphene; for each 0.001 molecular proportion of CaO that is used one obtains 0.20 weight per cent of sphene. For chlorite, MgO and FeO are allotted in the same ratio as they occur in the chemical analysis; for each 0.001 molecular proportion of MgO + FeO one allots 0.001 proportion of H_2O+, 0.0002 proportion of Al_2O_3, and 0.0006 proportion of SiO_2.

Zircon.—After the minor mineral constituents discussed above have been determined, the rest of the computation is made automatically on a mathematical basis. Zircon may be calculated on the assumption that all ZrO_2 in the rock is present in this mineral. Using molecular proportions, all ZrO_2 and an equal amount of SiO_2 are allotted to zircon. The weight per cent of zircon is determined from Johannsen (1931, vol. I, p. 252) or Washington (1917). In the rocks under consideration, however, the amount of ZrO_2 is so small that it does not amount to 0.001 molecular proportion. Under such circumstances zircon might be neglected or merely recorded as a trace. However, because of its importance as a possible source of radioactivity (Billings and Keevil, 1946, p. 810), some attempt should be made to determine the amount of zircon as accurately as possible. This can be done by using weights per cent in the computations rather than molecular proportions. All ZrO_2, in weight per cent, is allotted to zircon; half as much SiO_2 (strictly 0.49 as much SiO_2) as ZrO_2 is allotted to zircon. The amount of ZrO_2 and SiO_2 so allotted are added to give the amount of zircon in weight per cent. Wherever weights per cent are used in the calculations in Table 5, the amounts are shown in parentheses.

Sulfide.—The amount of sulfide in weight per cent is determined in a similar way. It is assumed that all the sulfur is present in pyrite. The spectrographic analyses (Table 3) show that other sulfides, such as those containing copper or lead, can be present only in very small amounts. All S and half as much FeO are allotted to pyrite, using molecular proportions. The amount of pyrite in weight per cent is determined by multiplying the molecular proportion of S by 60. In several of the rocks discussed in this paper the amount of S is so small that it does not represent even one molecular proportion. It could be neglected or sulfide could be recorded as a trace. Inasmuch as the amount of sulfide in the rocks, although small, is of some interest, it seems best to revert to the use of weights per cent rather than molecular proportions. All S, in weight per cent, is allotted to pyrite; 1.1 times as much FeO is also allotted to pyrite. The amount of pyrite present is 1.87 times the weight per cent of S. Although the total amount of S and FeO assigned to pyrite is 2.1 times the amount of S, the weight per cent of pyrite is only 1.87 times the amount of S. This discrepancy is due to the fact that the iron is allotted as if it were an oxide, but it is present in the pyrite as iron.

Apatite.—The weight per cent of apatite is calculated on the assumption that all the P_2O_5 is present in this mineral. All P_2O_5, in molecular proportions, is allotted to apatite; 3.3 times as much CaO as P_2O_5 and 0.33 times as much F_2 as P_2O_5 are also allotted to this mineral. The weight per cent of apatite can be obtained from tables such as those in Johannsen (1931, vol. I, p. 251) or Washington (1917). Where less

than 0.001 molecular proportion of P_2O_5 is present, one may revert to the use of weights per cent. All P_2O_5 in weight per cent is assigned to apatite; 1.3 times as much CaO and 0.09 times as much F_2, both in weight per cent, are also allotted to apatite. The molecular proportions that these weights represent should be entered in the Table. The amount of apatite, in weight per cent, is 2.3 times the amount of P_2O_5 in weight per cent.

Calcite.—If calcite is the only carbonate present in the rock, as is the case in the coarse syenite, then all CO_2, in molecular proportions, and an equal amount of CaO are allotted for this mineral. The weight per cent of calcite is obtained by multiplying the molecular number by 100 (Johannsen, 1931, vol. I, p. 253).

Magnetite, ilmenite, biotite, and hornblende.—Some TiO_2 and FeO have already been assigned to sphene and chlorite. The remaining TiO_2 and FeO, and all the Fe_2O_3, may now be assigned to magnetite, ilmenite, and biotite (plus hornblende if present). Let x = molecular proportions of FeO to be assigned to magnetite, y = molecular proportions of FeO to be assigned to ilmenite, and z = molecular proportions of FeO to be assigned to biotite (and hornblende if it is present). Let a = available FeO (that is, all FeO except that already used in chlorite); b = Fe_2O_3; c = available TiO_2 (that is, all TiO_2 except that already used in sphene); d = available MgO (that is, all MgO except that already used in chlorite). The following relations are then true:

$$x + y + z = a \tag{1}$$

$$x + r'(z + d) = b \tag{2}$$

$$y + r^t(z + d) = c \tag{3}$$

where r' is the ratio of Fe_2O_3 to (FeO + MgO) in the biotite (or biotite plus hornblende if the latter be present) and r^t is the ratio of TiO_2 to (FeO + MgO) in the biotite (or biotite plus hornblende if the latter is present).

The analyses in Iddings (1920, vol. I, tables at end) indicate that for biotite r' averages 0.08, although it ranges from 0.06 to 0.12 and in exceptional cases may be even larger. The analyses in Iddings indicate that for hornblende this figure averages 0.06, although it ranges from 0.03 to 0.08 and in exceptional cases is even higher. In an analyzed common hornblende from the Moosilauke quadrangle of New Hampshire, with optical properties similar to those characteristic of the hornblende in the Oliverian magma series of the Mt. Washington quadrangle, $r' = 0.04$ (Billings, 1937, p. 556). In the present paper this was the figure used for hornblende.

In rocks containing both biotite and hornblende, an interpolated figure was used, depending upon the ratio of biotite to hornblende as seen in thin section. Thus, for a rock containing biotite but no hornblende, $r' = 0.08$; for a rock containing equal amounts of biotite and hornblende it is 0.06; and for rocks containing 3 times as much hornblende as biotite the value is 0.05.

The factor r^t is the ratio of TiO_2 to (FeO + MgO) in the biotite (or biotite plus hornblende if the latter be present). The analyses in Iddings indicate that for biotite this value averages 0.07, although it ranges from 0.03 to 0.10. Iddings' analyses indicate that for hornblende this value averages 0.03, although it ranges from 0.018 to 0.040, and there are some more extreme values. In the New Hamp-

shire hornblende, referred to above, $r^t = 0.03$, the same as Iddings' average. For rocks containing both biotite and hornblende an interpolated figure is used. Thus, for a rock containing biotite but no hornblende $r^t = 0.07$; for a rock containing equal amounts of biotite and hornblende it is 0.05; and for a rock with three times as much hornblende as biotite it is 0.04.

If analyses of the biotite and hornblende from the rock have been made, r^f and r^t are known with precision.

After the values for x, y, and z have been determined, x molecular proportions of FeO and an equal amount of Fe_2O_3 are assigned to magnetite; y molecular proportions of FeO and an equal amount of TiO_2 are assigned to ilmenite. The usual tables, such as those in Washington and Johannsen, may be used to calculate the magnetite and ilmenite in weight per cent. z molecular proportions of FeO are reserved for biotite (or biotite plus hornblende if the latter is present); d molecular proportions of MgO are reserved for biotite (or biotite plus hornblende if the latter is present).

If biotite is present, but there is no hornblende, z molecular proportions of FeO and d molecular proportions of MgO are assigned to biotite. Other oxides are assigned to biotite in accordance with ratios that are averages for the biotites listed by Iddings, but the results would not differ significantly if the standard molecules given by Winchell (1933) were used. The amount of (FeO + MgO), in molecular proportions, is taken as unity; the other oxides are then allotted to biotite in the following ratios compared to (FeO + MgO): SiO_2, 1.22; Al_2O_3, 0.30; Fe_2O_3, 0.08; K_2O, 0.19; H_2O+, 0.43; TiO_2, 0.07; and F_2, 0.03.

If hornblende is present, but no biotite, z molecular proportions of FeO and d molecular proportions of MgO are allotted to hornblende. Other oxides are assigned to hornblende in appropriate ratios, all calculations being in molecular proportions; the ratios are the same as those for the analyzed hornblende from the Moosilauke quadrangle. The amount of (FeO + MgO) is taken as unity; the other oxides are then allotted in the following ratios relative to (FeO + MgO): SiO_2, 1.54; Al_2O, 0.21; CaO, 0.46; H_2O+, 0.33; Fe_2O_3, 0.04; TiO_2, 0.15; F_2, 0.01.

If analyses of the biotite and hornblende from the rock have been made, the ratios of the other oxides to (FeO + MgO) are known with precision.

If both biotite and hornblende are present, the weight per cent of the less abundant of these two minerals must be determined by a Rosiwal analysis. Suppose biotite is 5 per cent and hornblende 20 per cent of the rock. Enough FeO and MgO, taken in the same ratio as they are present in the rock after chlorite, magnetite, and ilmenite have been taken care of, are allotted to make the appropriate amount of biotite. Other oxides are allotted to biotite in the same ratios as indicated above. Several trial allotments may be necessary before the correct amount of (FeO + MgO) is chosen to give the correct amount of biotite. (*See* below.) The remaining FeO and MgO are allotted to hornblende, and the other oxides are then added in the ratios indicated above. If hornblende is the less abundant mineral, then enough (FeO + MgO), with other oxides in the right proportions, are allotted to make the correct amount of hornblende. The remaining FeO and MgO are then allotted to biotite, with other oxides in appropriate proportions.

The amount of biotite in weight per cent is determined by adding together the weights per cent of all the oxides assigned to this mineral. This may be done by using "in reverse" the tables in Johannsen (1931, vol. I, p. 241–245); for each molecular number one may determine the weight per cent represented. For greater precision one can multiply the molecular weight of each oxide by the molecular number assigned to the biotite. The amount of hornblende is determined in an identical way.

Feldspar, clay minerals, and sericite.—The next step is the allotment of oxides to the feldspar. All the remaining CaO is allotted to the anorthite molecule of plagioclase; using molecular proportions, an equal amount of Al_2O_3 and 2 times as much SiO_2 are also allotted to anorthite. The amount of soda to be assigned to plagioclase is determined according to the following equation:

$$b = \frac{a - a\,An}{2\,An}$$

Where b = number of molecules of albite to be assigned to plagioclase, a = number of molecules of anorthite already allotted to plagioclase, and An = anorthite content of plagioclase as determined by optical methods. The factor of 2 is placed in the denominator because in the tables given in Washington and Johannsen the albite molecule ($Na_2O \cdot Al_2O_3 \cdot 6\,SiO_2$) has twice the molecular weight of the albite molecule ($NaAlSi_3O_8$) used in the diagrams relating optical data to chemical composition.

For example, in the case of the biotite-quartz monzonite, as shown in Table 5, 0.017 molecular proportion of CaO is assigned to anorthite. Optical methods show that the anorthite content of the plagioclase is 0.17 per cent (the repetition of the figure 17 is a coincidence). Substituting in the equation given above:

$$b = \frac{0.017 - 0.017(0.17)}{2(.017)} = 0.0415$$

On this basis, 0.042 molecular proportion of Na_2O are allotted to the albite in the plagioclase; an equal amount of Al_2O_3 and 6 times as much SiO_2 are likewise allotted for this albite. The amounts of anorthite and albite, in weights per cent, in plagioclase are readily determined from the tables in Johannsen or Washington.

All remaining Na_2O is assigned to potash-soda feldspar, the Na_2O being matched by an equal amount of Al_2O_3 and 6 times as much SiO_2. BaO is assigned to the celsian molecule; an equal amount of Al_2O_3 and twice as much SiO_2 are also allotted to this molecule which is considered to be present in the potash-soda feldspar in solid solution. The next step would seem to be to assign all the remaining K_2O (that is, all that is left after the allotment to muscovite and biotite) to the orthoclase molecule. A preliminary study showed, however, that if this is done there is an unexplained excess of Al_2O_3. Moreover, a re-examination of the thin sections revealed that all the rocks contain some sericite and a clay mineral, which for purposes of calculation is assumed to be kaolin. Theoretically, the distribution of K_2O, Al_2O_3, and H_2O among orthoclase, sericite, and kaolin can be solved by a series of equations given by Washington (1918) and Holmes (1921, p. 403). The formulae for the three minerals are assumed to be: orthoclase, $K_2O \cdot Al_2O_3 \cdot 6\,SiO_2$; sericite, $K_2O \cdot 2\,H_2O \cdot 3\,Al_2O_3 \cdot 6\,SiO_2$; and kaolin $2\,H_2O \cdot Al_2O_3 \cdot 2\,SiO_2 \cdot$

Let a be the molecular amount of K_2O available, b be the molecular amount of H_2O+ available, and c be the molecular amount of Al_2O_3 available. By "available" is meant the amount of each of these oxides left after muscovite, chlorite, biotite, hornblende, anorthite, albite, and celsian have been taken care of. Let x, y, and z be the respective molecular amounts of orthoclase, sericite, and kaolin.

Then,

$$x + y = a \tag{1}$$

$$2y + 2z = b \tag{2}$$

$$x + 3y + z = c \tag{3}$$

These three equations are then solved to give x, y, and z. As Holmes (1921, p. 406) points out, the method is not reliable, because the molecular weight of H_2O is so low that a small change would unduly influence the calculation. Moreover, most of the rocks being considered in the present paper do not have enough H_2O+ to satisfy the requirements. It was therefore decided to adopt a somewhat different method. The problem would be greatly simplified, of course, if the amount of sericite and kaolin could be determined by Rosiwal analysis, but this is impossible for such small grains, many of which are smaller than the thickness of the thin section. However, the ratio of these two minerals can be readily estimated. The following equation can be established:

$$\frac{\textit{Molecular weight of kaolin}}{\textit{Molecular weight of sericite}} \times \frac{z}{y} = \frac{\textit{Specific gravity of kaolin}}{\textit{Specific gravity of sericite}} \times r$$

Where

$$r = \frac{\textit{Volume of kaolin}}{\textit{Volume of sericite}}$$

as seen in thin section.

This equation reduces to

$$\frac{z}{y} = 2.5r \tag{4}$$

Two alternate courses are now open. One is to use equations (1), (3), and (4). This is tantamount to assuming that enough H_2O+ is present to satisfy all the requirements, and that the analysis is incorrect insofar as it lacks H_2O+ to meet these requirements. In this case the available K_2O, H_2O+, and Al_2O_3 would be distributed among orthoclase, sericite, and kaolin; there would be no excess Al_2O_3. The alternate course is to assume that the H_2O+ determinations are correct and to use equations (1), (2), and (4). This ditributes K_2O, Al_2O_3, and H_2O+ among orthoclase, sericite, and kaolin, but in most cases also leaves an unaccountable excess of Al_2O_3. This latter method was the one adopted, as it seems to be the more objective one. In the specimens considered in this paper the excess Al_2O_3 averages 0.6 per cent, and the maximum is 1.0 per cent. If the water determination is actually too low, the rocks would have somewhat more sericite and kaolin than indicated by the modes given in Table 6.

After the equations have been solved, appropriate amounts of K_2O, Al_2O_3, SiO_2, and H_2O+ are allotted to orthoclase, sericite, kaolin, and excess Al_2O_3.

The weights per cent of albite and orthoclase in the potash-soda feldspar are determined from the tables in Johannsen or Washington. The weight per cent of celsian is determined by multiplying the number of molecular proportions of BaO by 375. The weight per cent of sericite is obtained by multiplying the molecular proportions of K_2O allotted to this mineral by 796. The weight per cent of kaolin is obtained by multiplying the molecular proportions of Al_2O_3 allotted to this mineral by 258.

One final adjustment in the feldspars is necessary. It is customary in giving modes to classify microperthite, as well as orthoclase and microcline, as potash-soda feldspar. There is very little microperthite in the Oliverian magma series of the Mt. Washington quadrangle, and the problem is not serious. The amount of plagioclase present as perthite lamellae in the potash-soda feldspar should be determined by the Rosiwal method and recalculated into weight per cent. This figure is then subtracted from the plagioclase and added to the potash-soda feldspar. It so happens that there is no microperthite in the biotite-quartz monzonite given in Table 5. In the coarse syenite, however, 3 per cent of the rock consists of perthitic plagioclase lamellae in the potash-soda feldspar. The weight per cent of plagioclase was calculated to be 26.4, and that of potash-soda feldspar to be 57.1. The final figures, however, after correction for the perthite lamellae, are 23.4 per cent plagioclase and 60.1 per cent potash-soda feldspar. This method assumes that the perthite lamellae are the same composition as the plagioclase throughout the rest of the rock. In the present study this is justified. If, however, the difference were great, a further adjustment would be necessary.

Quartz.—The remaining SiO_2 is assigned to quartz. To determine the amount of quartz in weight per cent, the number of molecular proportions of SiO_2 are multiplied by 60.

Totals.—The weights per cent of the minerals are totalled and then recalculated to 100.0 per cent. In general, the results are expressed to the first decimal point, although it is recognized that this figure is not significant, as will be shown below. Zircon, however, is given to the second decimal, in view of the fact that, although in small quantities, it is readily recognized in thin section.

ERRORS AND LIMITS OF ACCURACY

General statement.—Such a method as that employed in the present paper is subject to errors. Sometimes modes calculated in this or some similar way are given to the second decimal place. At the other extreme, some authors express grave doubts as to the significance of the results. It seems highly desirable, therefore, to give some discussion of the accuracy of the results.

Size of sample.—The samples that are sent to the chemical analyst to be crushed must exceed a minimum size, which depends upon the size of the minerals in the rock. Larsen (1938, p. 99–100) has shown that if the grains are cubes 0.1 cm. on a side, the specimen must weigh 2.7 gms. to insure a probable error of not over 0.1 per cent in sampling the minerals. If the grains are 1 cm. on a side, the specimen must weigh 2700 gms., which is 8 times the size of the average hand specimen. The Rock Analysis Laboratory of the University of Minnesota also gives instructions concerning the size of the specimen required, and in all cases these were followed.

Accuracy of analyses.—The accuracy of the chemical analysis is of prime importance. There is every reason to believe that both the regular analyses and the spectroscopic analyses accompanying this paper are of the highest quality. The totals of all the regular analyses fall well within the limits of good analyses, but, as Larsen (1938, p. 98) states: "... it is inevitable that many of the determinations are out as much as 0.10 per cent and some are out much more." The error in calculating the weight per cent of a mineral might be several times these figures; if K_2O were present only as orthoclase, an error of 0.10 per cent in this oxide would give an error of over 0.5 per cent in the mineral.

Incompleteness of the regular analyses.—The regular analyses in Table 2 are incomplete, and the spectrographic data in Table 3 show that the regular analyses would have been different if complete analyses had been run. As pointed out on a previous page, this is quantitatively important only for BaO, Li_2O, and SrO. BaO, however, has been used in the calculation of the modes. SrO, which ranges from 0.08 to 0.4 in the spectrographic analyses, comes down as CaO in the regular analyses. Presumably, much of the SrO is present in the hornblende, but in the calculations it was treated as if it were CaO. Obviously a small error is introduced by this assumption. Similarly, Li_2O comes down as Na_2O; the Li_2O is probably present in biotite, whereas it was assumed that the Na_2O was present in the albite molecule. If a rock contained 0.06 per cent Li_2O that had been reported as Na_2O, the amount of albite in the mode would be 0.52 per cent too high.

The calculated modes show an excess of Al_2O_3 ranging from 0.0 to 1.0 per cent. As pointed out in a previous section, Cr_2O_3, SnO, ZrO_2, and Sc_2O_3 appear as Al_2O_3 in the regular analyses; the same is partially true of Co_2O_3, NiO, PbO, V_2O_5, and B_2O_3. The total for all these oxides ranges from a minimum of 0.021 per cent to a maximum of 0.086 per cent. It is obvious, therefore, that this factor does not account for the excess Al_2O_3.

Use of molecular proportions.—Although the use of molecular proportions greatly facilitates the calculations, it is less precise than it would be to assign the oxides by weights per cent. An inspection of the tables entitled *Percentage weights for numbers of molecules of the normative minerals* (Washington, 1917, Appendix 5, p. 1172–1180; Johannsen, 1931, vol. I, p. 236–253) shows that there is a certain amount of "slack" in the method. The amount of orthoclase, for example, is always some multiple of 0.556, given to the nearest second decimal, such as 0.56, 1.11, 1.67, *etc.* The error in determining orthoclase may be slightly greater than 0.30 weight per cent, due to this factor alone. Let us suppose that the weight per cent of potash in the rock is 0.24 and that all of it is to be assigned to orthoclase. Calculating by weights per cent we determine the amount of orthoclase to be 1.42 weight per cent. By using molecular proportions, 0.24 weight per cent of K_2O becomes converted to 0.002 molecular proportion, and this in turn gives 1.11 weight per cent of orthoclase. The error is thus 0.31 weight per cent. It is true that this is probably the maximum error for orthoclase due to this factor. Moreover, orthoclase, because of its high molecular weight, gives one of the highest errors. For any mineral the maximum possible error in weight per cent due to this factor alone is approximately half the molecular weight of the mineral divided by 1000. Thus, the following are approximately the maximum possible errors, in weight per cent, due to the use of molecular

proportions: albite, 0.26; anorthite, 0.14; magnetite, 0.11; ilmenite, 0.08; apatite, 0.17; sphene, 0.10; calcite, 0.05; muscovite and sericite, 0.40; quartz, 0.03; biotite, 0.10; hornblende, 0.11. Niggli (1936) and Barth (1945, p. 10) have advocated using atomic percentages in all petrographic calculations. Whatever the advantages of Niggli's system, the "slack" is even greater than in the method employing molecular proportions.

Use of theoretical minerals.—Obviously an error is introduced into the calculations by assuming "ideal" minerals. Thus definite ratios have been assumed between the different oxides in each mineral, such as the 1:1:6 ratio among K_2O, Al_2O_3, and SiO_2 in orthoclase. Actually, of course, all minerals deviate from these hypothetical minerals. Plagioclase contains some potash, and potash-soda feldspar contains some lime; no allowance has been made for this in the calculations. On the average, plagioclase contains about 6 per cent orthoclase, whereas potash-soda feldspar contains about 4 per cent anorthite. The two errors thus tend to compensate each other if plagioclase and potash-soda feldspar are present in about equal amounts. It is obvious, however, that due to this cause the error in the calculated amounts of plagioclase and potash-soda feldspar may be several weights per cent.

Muscovite contains iron and magnesia, for which no allowance has been made. However, inasmuch as this mineral is generally present in small amounts, the error so introduced is not great.

The amounts of magnetite, ilmenite, and biotite have been calculated on the basis of the amounts of Fe_2O_3, FeO, TiO_2, and MgO available, after such minerals as chlorite, sphene, and pyrite have been taken care of. Moreover, it was necessary to assume that the Fe_2O_3 in the biotite was 0.08 per cent of the amount of available (FeO+MgO); similarly, it was necessary to assume that the TiO_2 in the biotite was 0.07 per cent of the amount of available (FeO + MgO). The greater the deviation of the actual ratios in the biotite in the rocks under consideration, the less reliable are the calculations. The ratio of TiO_2 (FeO + MgO) ranges in most biotites from 0.03 to 0.10; the ratio of Fe_2O_3 to (FeO + MgO) ranges from 0.06 to 0.12. Trial calculations show that the error in magnetite will probably not exceed 10 per cent of the amount of biotite; that is, if the rock contains 5 per cent biotite, the calculated amount of magnetite may be in error 0.5 weight per cent. The error is the same for ilmenite. The error in biotite will not exceed the sum of the errors for magnetite and ilmenite, and may be considerably less if the errors are compensating. Thus, if the biotite is calculated from the equations given above to be 5.0 per cent, the magnetite to be 1.0 per cent and ilmenite to be 1.0 per cent, the actual values considering just this one type of error, might be 6.0, 0.5, and 0.5 per cent.

After FeO, Fe_2O_3, TiO_2, and MgO have been assigned to biotite in accordance with the equations discussed above, the other oxides, such as K_2O, Al_2O_3, SiO_2, and H_2O+ are allotted in accordance with an arbitrary formula. Any deviation of the actual ratios from those assumed will introduce an error into the estimated weight per cent of biotite. Assuming that Iddings' analyses *a* to *e* (Iddings, 1920, table opposite p. 454) are representative of the range to be expected in the biotites in plutonic rocks, calculations show that the probable maximum error in the total amount of biotite would not exceed 0.07 per cent for each 1.0 per cent of biotite; that is, 7 per cent of

the total amount of biotite. The maximum probable error, therefore, in rocks under consideration, due to this factor alone, is 0.4 weight per cent.

The total error in estimating the amount of biotite due to the uncertainties in its composition could be as much as 1.5 per cent for each 5 per cent of biotite.

In general the statements made above for biotite would hold for hornblende.

Accuracy of Rosiwal analyses.—The problem of the accuracy of the Rosiwal method enters into the present problem only to a limited extent: (1) the determination of the weights per cent of a few of the minor constituents; (2) comparison of the results obtained by the methods outlined in the present paper with the results obtained by Rosiwal analyses.

It was necessary to calculate the weight per cent of a few of the minor constituents, such as muscovite, sphene, chlorite, and in some instances biotite, by the Rosiwal method. It was, of course, necessary to make a complete Rosiwal analysis of all the constituents in such rocks in order to recalculate the volumes per cent into weights per cent. Larsen and Miller (1935) have studied this problem and reached two significant conclusions. In a single thin section the weights per cent of the minerals may be determined with an error that is not greater than one; that is, if quartz is calculated to be 30 per cent, it may actually be 29 or 31 per cent. Different thin sections from the same hand specimen, however, may show considerable variation, the major constituents differing by as much as nearly 10 per cent and occasionally more than 20 per cent. In the present investigation, two thin sections were cut perpendicular to each other from the same chip of coarse syenite. The weights per cent of some of the minor constituents (sphene, opaques, biotite, and hornblende) in the two thin sections were averaged. The measured amount of the same mineral in the two different sections varied considerably; sphene, for example was 1.0 weight per cent in one section, but 1.6 per cent in the second; the average was 1.3 weight per cent. It is apparent that data obtained from a single thin section are not necessarily representative. Such inaccuracies not only cause errors in the weights per cent of the minerals that are determined by the Rosiwal method, but also produce errors in other minerals containing the same elements.

Comparison of the results obtained by the method outlined in the present paper with those obtained by the Rosiwal method is reserved for a later section.

Accuracy of determining anorthite content of plagioclase.—A surprisingly large error is introduced into the calculated mode by a slight error in the determination of the anorthite content of the plagioclase. It will be recalled that the equation used is:

$$b = \frac{a - aAn}{2An}$$

where b = number of molecules of albite to be assigned to plagioclase, a = number of molecules of anothite already alloted to plagioclase, and An = anorthite content of plagioclase as determined by optical methods.

As an example, we may take a case in which $a = 20$, and $\alpha = 1.536$, indicating that $An = 0.17$. Then b will be 49, and 25.68 weight per cent of albite are assigned to plagioclase. If, however, α were erroneously measured as 1.538, implying that $An = 0.20$, then b would be erroneously calculated to be 40, and only 20.96 weight

per cent of albite would be assigned to plagioclase. Thus 4.72 weight per cent too little albite would be assigned to plagioclase, and 4.72 weight per cent too much albite would be assigned to potash-soda feldspar. A small error in measuring the indices thus causes a large error in calculating the amount of plagiclase and potash-soda feldspar. This error is a function of the albite content of the plagioclase; in sodic

TABLE 7.—*Difference between modes calculated from chemical analyses and average modes determined from thin sections*

	(1)	(2)	(3)	(4)	(5)	(6)
Quartz	−12.8	+0.7	−4.3	−1.0	+2.3	+3.1
Potash-soda feldspar	+8.5	+4.3	+3.1	−1.5	−0.9	+0.7
Plagioclase	−7.4	−2.4	−5.6	+3.1	−2.4	−2.2
Biotite	+1.3	−4.3	+1.0	+0.2	−0.8	−0.8
Hornblende	+7.6	.....	−0.7	.....	.....	.....
Muscovite	.....	+0.3	.....	.....	+0.6	−1.2
Opaques	+0.9	−0.9	+1.0	−1.2	−0.5	−0.6
Sphene	0.0	.....	+1.3	−0.6	.....	.....

1. Hornblende monzonite facies of hornblende-quartz monzonite.
2. Fine-grained gray quartz monzonite.
3. Coarse syenite.
4. Coarse granite.
5. Biotite-quartz monzonite.
6. Porphyritic biotite-quartz monzonite.

oligoclase and albite the error is very large, but becomes progressively less with increasing anorthite content of the plagioclase. In the rocks of the Oliverian magma series of the Mt. Washington quadrangle an error of two in the third decimal place in measuring the index would give an error of 2 to 5 weight per cent in calculating the amounts of plagioclase and potash-soda feldspar; the errors would be complementary.

Summary of errors.—It is difficult to state with precision the probable total error in the method of calculation adopted in this paper. Tabulation of the data given above suggests that if the errors were cumulative they would have the following maximum values: for minerals making up 1 weight per cent of the rock, the error might be 0.5 weight per cent; for minerals making up 6 weight per cent of the rock, the error might be 2 weight per cent; and for minerals making up 30 to 60 weight per cent of the rock, the error might be as great as 7 weight per cent. The actual total errors are probably much less than this, because compensating errors are involved.

Test of accuracy.—One test of the accuracy of the results presented here and those given in the paper by Chapman, Billings, and Chapman (1944) is given in Table 7. In this table the weight per cent of each mineral as given in Table 1 (the average modes in weight per cent based on thin sections) have been subtracted from the figures given in Table 6 (the modes as calculated from the chemical analyses) Column two of Table 7, for example, indicates that quartz, as calculated from the chemical composition, is 0.7 weight per cent higher than quartz in the average of the modes as estimated from thin sections. Potash-soda feldspar was calculated from the chemical analyses to be 4.3 weight per cent higher than the average found in the

thin sections. A plus sign indicates that the modal mineral calculated from the chemical analysis is greater than that determined from the thin sections, whereas a negative sign shows the reverse.

With the exception of column 1, which is the hornblende-quartz monzonite, the two methods agree reasonably well. As pointed out in previous papers, the hornblende-quartz monzonite is very variable, and when the specimen was sent for analysis it was realized that the sample chosen was not very representative of the type. The five other rocks show good agreement. The minor constituents fail to check as well as they might, inasmuch as the figures given in Table 1 are in round numbers, and no decimals were used. The agreement between the two methods shown by Table 7 indicates several things: (1) the average modes given in the paper by Chapman, Billings, and Chapman (1944) seem to be reasonably accurate; (2) the specimens chosen for chemical analysis were representative of these averages, with the exception of the hornblende-quartz monzonite; and (3) the method of calculating the modes from the chemical analysis is fairly accurate, presumably as accurate as the results obtained from the Rosiwal analysis of a single thin section or the separation of the different minerals by heavy liquids.

SUMMARY

Complete chemical analyses, including spectrographic determination of 44 trace elements, have been made for the six map units of the Oliverian magma series in the Mt. Washington quadrangle of New Hampshire. The silica content of these rocks ranges from 55.83 to 75.08 per cent. The rocks are unusually rich in potash, which attains a maximum value of 7.19 per cent in the coarse syenite. The principal oxides show the usual variation diagram: alkalies and alumina reach a maximum in the syenite, but lime, magnesia, and total iron decrease toward the siliceous end of the series.

Although many of the trace elements show no systematic change with increasing silica content, Cr_2O_3, NiO, SrO, V_2O_5, and BaO decrease with increasing silica content; ZnO increases with increasing silica. Compared with similar rocks elsewhere in the world, the Oliverian magma series appears to be richer in some trace elements, such as SrO, Sc_2O_3, Li_2O, NiO, V_2O_5, and, to a slight extent, BaO. Ga_2O_3, La_2O_3, Rb_2O, and perhaps Y_2O_3 appear to be less abundant in the Oliverian magma series than on the average elsewhere.

Modes calculated from the chemical analyses are presented, with a discussion of the methods used and the probable errors. Although there are several sources of error in these computations, inasmuch as the results compared favorably with those obtained from the study of thin sections, it is believed that the method is relatively accurate. An unexplained excess of Al_2O_3 in the analyses, ranging from 0.0 to 1.0 per cent may be due to the presence of more kaolin and sericite than seems likely, but if so the H_2O+ determination in most of the rocks is too low.

REFERENCES CITED

Barth, Tom. F. W. (1945) *Studies on the igneous rock complex of the Oslo region, II. Systematic petrography of the plutonic rocks*, Skrifter Utgitt av det Norske Videnskap-Akademi i Oslo, I. Mat. Naturv. Klasses. 1944. No. 9.

Billings, M. P. (1937) *Regional metamorphism of the Littleton-Moosilauke area, New Hampshire*, Geol. Soc. Am., Bull., vol. 48, p. 463–566.

———, Chapman, C. A., Chapman, R. W., Fowler-Billings, K., and Loomis, F. B., Jr. (1946) *Geology of the Mt. Washington Quadrangle, New Hampshire*, Geol. Soc. Am., Bull., vol. 57, p. 261–274.

———, and Keevil, N. B. (1946) *Petrography and radioactivity of four Paleozoic magma series in New Hampshire*, Geol. Soc. Am., Bull., vol. 57, p. 797–828.

Bray, J. M. (1942) *Spectrographic distribution of minor elements in igneous rocks from Jamestown, Colorado*, Geol. Soc. Am., Bull., vol. 53, 765–814 pages.

Chapman, C. A., Billings, M. P., and Chapman, R. W. (1944) *Petrology and structure of the Oliverian magma series in the Mount Washington quadrangle, New Hampshire*, Geol Soc. Am., Bull., vol. 55, p. 497–516.

Goldschmidt, V. M. (1937) *The principles of distribution of chemical elements in minerals and rocks*, Jour. Chem. Soc., p. 655–673.

Hadley, J. B. (1942) *Stratigraphy, structure, and petrology of the Mt. Cube area, New Hampshire*, Geol. Soc. Am., Bull., vol. 53, p. 113–176.

Holmes, A. (1921) *Petrographic methods and calculations*, 506 pages.

Iddings, J. (1920) *Igneous rocks*, 2d ed., vol. 2, New York.

Johannsen, A. (1931) *A descriptive petrography of the igneous rocks*, vol. I, 267 pages, Chicago.

Kemp, J. F., and Grout, F. F. (1940) *A handbook of rocks*, 6th ed., second printing, New York, 300 pages.

Larsen, E. S., Jr. (1938) *The accuracy of chemical analyses of amphiboles and other silicates*, Am. Jour. Sci., 5th ser., vol. 35, p. 94–103.

———, and Miller, F. S. (1935) *The Rosiwal method and the modal determination of rocks*, Am. Mineral., vol. 20, p. 260–273.

Niggli, P. (1936) *Uber Molekularnormen zur Gesteinsberechnung*, Schweiz. Min. Petr. Mitt., vol. 16, p. 295–317.

Rankama, K. (1946) *On the geochemical differentiation in the earth's crust*, Comm. Géol. Finlande, Bull. no. 137, 39 pages.

Sahama, Th. G. (1945) *Spurenelemente der Gesteine im Sudlichen Finnich-Lappland*, Comm. Géol. Finlande, Bull., no. 135.

Sandell, E. B., and Goldich, S. S. (1943) *The rarer metallic constituents of some American igneous rocks*, Jour. Geol., vol. 51, p. 99–115, 167–189.

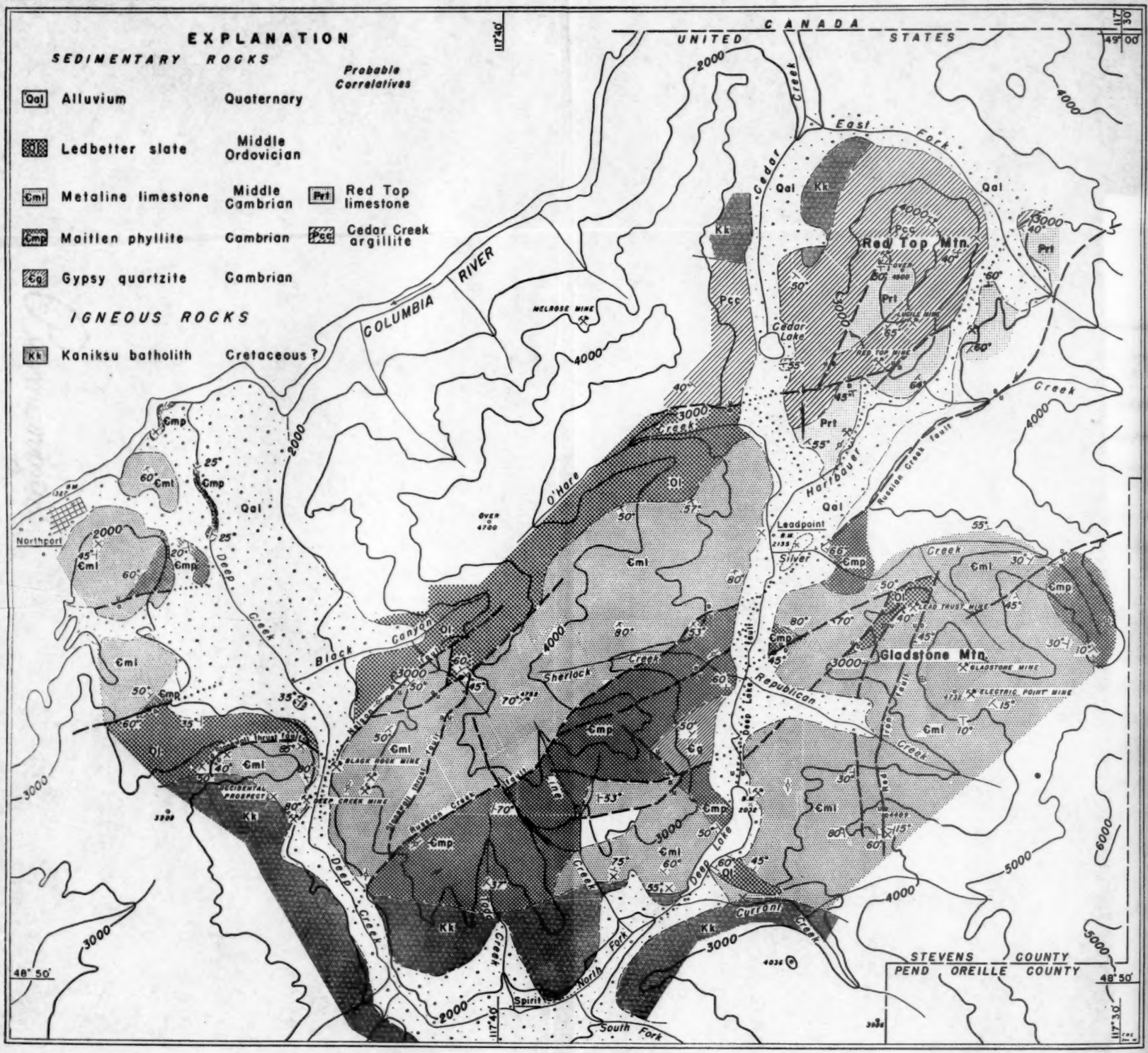
Shimer, J. A. (1943) *Spectrographic analysis of New England granites and pegmatites*, Geol. Soc. Am., Bull., vol. 54, p. 1049–1066.

Washington, H. S. (1917) *Chemical analyses of igneous rocks*, U. S. Geol. Survey, Prof. Paper 99, 1201 pages.

——— (1918) *The calculation of the "rational analysis" of clays*, Jour. Am. Ceramic Soc., vol. 1, p. 405–421.

Winchell, A. N. (1933) *Elements of optical mineralogy, Pt. II*, 459 pages.

Geological Museum, Oxford St., Cambridge 38, Mass.; U. S. Geological Survey, Washington 25, D. C.
Manuscript received by the Secretary of the Society, September 26, 1946.



Scale

1 0 1 2 3 MILES

CONTOUR INTERVAL 1000 FEET

TOPOGRAPHY AND GEOLOGY OF THE NORTHPORT DISTRICT

Topography adapted from Colville quadrangle. Geology transferred from aerial photograph field sheets.

117°30'
49'
30'
8°50'
117°30'

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 58, PP. 597-612, 1 PL., 1 FIG. JULY 1947

CAMBRIAN ROCKS OF NORTHEASTERN STEVENS COUNTY, WASHINGTON

BY CHARLES D. CAMPBELL

CONTENTS

	Page
Abstract	598
Introduction	598
Location	598
Scope and purpose of report	599
Field work	599
Acknowledgments	599
Summary of earlier work	599
Use of new formation names	600
Metaline limestone	602
Distribution	602
Stratigraphic sections	603
General statement	603
Gladstone Mountain section	603
Lower Deep Creek section, east side	603
Lower Deep Creek section, west side	604
Lithology and internal structure	604
Age and correlation	606
Maitlen phyllite	606
Distribution	606
Stratigraphic sections	607
General statement	607
Sherlock Creek section	607
Lithology and internal structure of Maitlen phyllite	607
Age and correlation	608
Gypsy quartzite	608
Distribution	608
Thickness and lithology	608
Age and correlation	609
Cedar Creek argillite	609
Distribution	609
Stratigraphic sections	609
General statement	609
Red Top Mountain section	609
Cedar Lake section	610
Age and correlation	611
Conclusions	611
Structural setting	611
References cited	612

ILLUSTRATIONS

Figure	Page
1. Index map of Washington and northern Idaho	598
Plate	**Facing page**
1. Topography and geology of the Northport district	597

ABSTRACT

Most of the marine metasedimentary rocks of northeastern Stevens County are tentatively correlated with three of the Cambrian formations established by Park and Cannon (1943) in the Metaline quadrangle, immediately to the east. Of the established Cambrian succession, the formations of northeastern Stevens County include the Metaline limestone, Maitlen phyllite, and the upper half of the Gypsy quartzite. Contacts are gradational. Fossils are scarce, and most of the correlations are based on lithology.

The Metaline limestone appears to be over 6000 feet thick and underlies the Ordovician Ledbetter slate. The brachiopods, *Nisusia* sp. and *Acrotreta* sp., were found near the middle of the formation on Gladstone Mountain. They indicate, according to Bridge, an early Middle Cambrian age, as do the trilobites found at a lower horizon in the Metaline quadrangle. The upper third of the formation is fine-grained, locally cherty calcite and dolomite marbles. The central third is white sugary dolomite marble with many beds of darker dolomite. Near shear zones much tremolite has formed. The basal third consists of alternations of gray limestone and phyllite beds.

The Maitlen phyllite, over 3700 feet thick, includes black, gray, and green phyllites and a quartzite unit.

The Gypsy quartzite includes 2500 feet of arkosic and micaceous quartzite with a few marble beds.

The Cedar Creek argillite, over 2800 feet thick, is probably correlative with the Maitlen phyllite and the Red Top limestone with the Metaline limestone.

INTRODUCTION

LOCATION

The area described in this report is in the northeast corner of the Colville quadrangle of northeastern Washington and includes a large part of the Northport mining district (Fig. 1). Adjoining it on the east is the Metaline quadrangle.

SCOPE AND PURPOSE OF REPORT

This report describes the westward extensions of the Cambrian formations recently named in the Metaline quadrangle (Park, 1938, p. 713; Park and Cannon, 1943, p. 6, 13–19). The report also proposes that the Metaline formation names supplant an earlier set of names within this part of Stevens County (Weaver, 1920, p. 46, 50, 53–54). This substitution is intended to simplify the problems of correlation in the nearly unfossiliferous Cambrian rocks of northeastern Washington.

FIELD WORK

Most of the field work was done in the autumns of 1942 and 1944 in connection with an examination of the lead and zinc resources of the Northport district for the U. S. Geological Survey.

Field notes were plotted on enlargements and contact prints of vertical aerial photographs, but many mineralized areas were mapped with the plane table.

ACKNOWLEDGMENTS

William Stoll and Irvin Gladstone of the Geological Survey, and Frank Paparich of Northport were indispensable in the field, and their help is gratefully acknowledged.

The writer's ideas about problems of geologic relationships in the area were greatly clarified by discussions with E. T. McKnight, C. F. Park, Jr., J. J. Collins, and M. G. Dings of the Geological Survey. W. A. G. Bennett of the Washington Division of Mines and Geology very generously pointed out some of the major unpublished results of his intensive work in the Cambrian rocks of central Stevens County. Only the published phases of his work will be referred to in this paper, however.

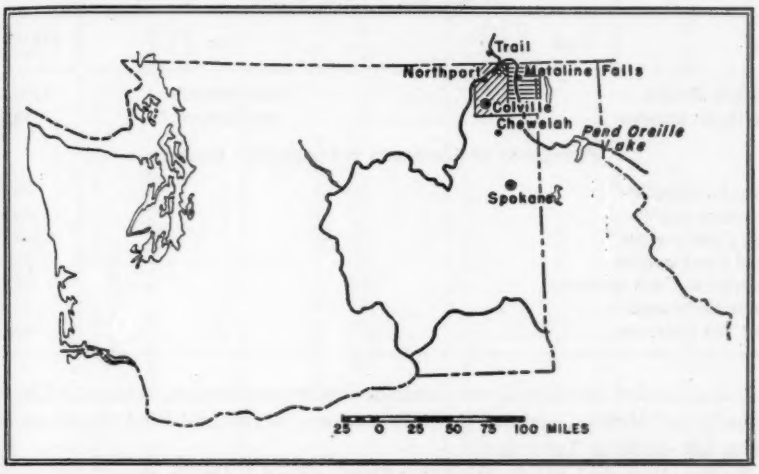


FIGURE 1—*Index map of Washington and northern Idaho.*
Colville quadrangle represented by diagonal lines; Northport district represented by cross hatching; Metaline quadrangle represented by horizontal lines.

SUMMARY OF EARLIER WORK

Before 1928, correlations of Cambrian rocks in northeastern Washington and adjoining areas had to be made on a lithologic basis as no fossils had been discovered.

Daly (1912, Table VIII., p. 178) considered the upper 13,650 feet of the Summit series, along the International Boundary, to be Cambrian. Conformably below are Beltian rocks, and conformably above is the "Pend D'Oreille group", the lower schists of which Daly believed to be of Silurian age (Daly, 1912, p. 276).

Weaver (1920), p. 49–84) recognized and mapped in Stevens County 18 Paleozoic formations which he called the Stevens series. He supposed that the Stevens series represented Daly's "Pend D'Oreille group" and possibly some of the Summit series; but as he could not be certain, he named as formations only lithologic units, most of them near their type areas (Weaver, 1920, p. 49–50). Eleven of these formations were believed to form a chronologic sequence of which the two youngest, the Mission argillite and the Northport limestone, occur in the Northport district. These two formations and possibly the next older ones were thought to be correlatives of the "Pend D'Oreille group", and thus possibly Upper Paleozoic (Weaver, 1920, p. 50). The older formations of the Stevens series were thought to be possibly Middle and Lower Paleozoic.

Seven additional named formations, all in the Northport district, were not assigned positions in the Stevens series, although Weaver (1920, p. 46, 54) supposed that they

were correlatives of the younger formations of the chronologic succession. The names and thicknesses of these are included in Table 1.

Reports on the economic geology of northeastern Stevens County (Bancroft, 1914, p. 51–59; Patty, 1921, p. 91–117; Jenkins, 1924, p. 27–28, 81–109) have furnished no new stratigraphic data.

TABLE 1.—*Formations in northeastern Stevens County*
(Weaver, 1920, Pl. 1, p. 46, 50, 53-54)

NAME	AGE	THICKNESS (feet)
Mission argillite	Late Paleozoic?	12,000
Northport limestone	Late Paleozoic?	3000
FORMATIONS OF UNCERTAIN STRATIGRAPHIC POSITION:		
Deep Lake argillite	?	2500
Boundary argillite	?	4000
Fish Creek argillite	?	1500
Lead Point argillite	?	2200
Republican Creek limestone	?	1200
Cedar Creek argillite	?	2500
Red Top limestone	?	1000

During the last 20 years, Lower Cambrian fossils have been found in central Stevens County, and Middle Cambrian fossils in northern Stevens and Pend Oreille counties. These are listed in Table 2.

Walker (1934, p. 3–5) concluded that Daly's "Pend D'Oreille group" and Summit series in the Salmo map area, British Columbia, immediately northeast of the Northport district, are correlatives of the late pre-Cambrian Windermere strata of Kootenay Lake.

Culver (1936, p. 51–52) announced the discovery of 44 fossil localities in the Stevens series of Stevens and Pend Oreille counties. Several of these are included in Table 2.

Park (1938, p. 712–716) and Park and Cannon (1943, p. 5–23) established in the Metaline quadrangle the stratigraphic succession of pre-Cambrian and Paleozoic rocks shown in Table 3. The names of the Cambrian formations are the ones adopted for this paper.

USE OF NEW FORMATION NAMES

The formation names used in the Metaline quadrangle (Table 3) are used in this report instead of those proposed by Weaver for the Northport district (Table 1).

The following are reasons for replacing Weaver's names:

(1) Several fossil collections have been made in two of the formations of the Northport district, allowing certain correlation with the same formations in the Metaline quadrangle.

(2) Lithologic sequences of these and underlying formations correspond well.

(3) Some formations proposed by Weaver include rocks of more than one geologic

TABLE 2.—*Cambrian fossil collections in northeastern Washington*

Age	Fossils	Stratigraphic position	Location	References
MIDDLE CAMBRIAN	*Nisusia* sp. *Hyolithes* sp. *Agnostus* sp.	Limestone pebbles in conglomerate forming top of Colville quartzite.	"At Kettle Falls, 10 miles west of Colville". Should be 5 miles NW. of Colville.	Resser, 1934, p. 7-8.
	Elrathia kingi *Pagetia* cf. *bootes* *Kootenia* sp. *Nedemus* sp. *Acrothele* sp.	Near base of Metaline limestone.	1 mile SE. of Metaline Falls.	Resser, 1934, p. 6-7. Park and Cannon, 1943, p. 19. Howell, 1945
PROBABLY LOWER OR MIDDLE CAMBRIAN	Trilobite fragments	Top of Gypsy quartzite.	12 miles NE. of Metaline Falls.	Park and Cannon, 1943, p. 15.
	Trilobite	Top of Metaline limestone.	1 mile N. of Metaline Falls, in Pend Oreille mine.	Park and Cannon, 1943, p. 19.
LOWER CAMBRIAN	*Kutorgina cingulata* (Billings) Pelecypod	"Undifferentiated limestone", probably basal part of Old Dominion limestone.	4 miles N. of Chewelah.	Jones, 1928, p. 115. Branson, 1931. Resser, 1934, p. 7. Bennett, 1941, p. 9.
	Archeocyathus Olenellid trilobite, possibly *Wanneria*	"Undifferentiated argillite".	1 mile N. of Colville.	Resser, 1934, p. 7.
PROBABLY LOWER CAMBRIAN	Brachiopods Pelecypods Trilobites	"Undifferentiated limestone", probably Old Dominion limestone.	13 miles NW. of Chewelah.	Jones, 1928, p. 115.
	Brachiopods	1500 feet below top of Addy quartzite, which underlies Old Dominion limestone.	8 miles NW. of Chewelah.	Bennett, 1944, p. 31.

TABLE 3.—*Formations in the Metaline quadrangle*
(Park and Cannon, 1943, p. 6)

NAME	AGE	THICKNESS (feet)
Limestone	Devonian	700
Ledbetter slate	Ordovician	2500
Metaline limestone	Middle Cambrian	3000
Maitlen phyllite	Lower or Middle Cambrian	5000+
Gypsy quartzite	Lower or Middle Cambrian	5300–8500
Monk formation	Cambrian?	3800+
Unconformity		
Leola volcanics	Pre-Cambrian	5000+
Shedroof conglomerate	Pre-Cambrian	5000+
Unconformity		
Priest River group	Pre-Cambrian	?

TABLE 4.—*Correlation of Cambrian rocks in the Northport district*

CAMBRIAN FORMATION	EQUIVALENT FORMATION IN STEVENS SERIES*
Metaline limestone	Northport limestone, in large part. Republican Creek limestone: in part, on lower Deep Creek and on Gladstone Mountain. Boundary argillite: in part, a band southwest from Leadpoint. Deep Lake argillite: in large part, west and northeast of Deep Lake Red Top limestone (?): entire. Doubtful correlation.
Maitlen phyllite	Northport limestone: in small part, small areas near Northport. Boundary argillite (?): in part, west of Cedar Lake, and a band southwest from Sherlock Creek. Deep Lake argillite: in small part, head of Silver Creek. Cedar Creek argillite (?): entire. Doubtful correlation.
Gypsy quartzite	Boundary argillite: in small part, an area northwest of Deep Lake.

* For locations of the areas mentioned, see Pl. 1.

period. For example, the Boundary argillite and Deep Lake argillite include both Cambrian and Ordovician rocks.

(4) Rocks of one geologic period are found in several of the earlier divisions. For example, the Ordovician Ledbetter slate forms a part of the Boundary argillite, the Deep Lake argillite, and the Lead Point argillite.

The simplification effected by this substitution is suggested in Table 4.

METALINE LIMESTONE

DISTRIBUTION

Three belts of Metaline limestone, 1 to 3 miles wide, trend northeast within the Northport district (Pl. 1). The southeast belt extends from the batholith, near Deep Lake, across Gladstone Mountain, and is flanked on both the northwest and northeast by Maitlen phyllite.

The middle belt also starts at the batholith, about 5 miles southeast of Northport,

and extends northeast at least 7 miles to the vicinity of Leadpoint. If Weaver's Red Top limestone is a correlative of the Metaline limestone, the middle belt can be extended 5 miles farther northeast; and an isolated area appears in the core of a syncline on Red Top Mountain, surrounded by Cedar Creek argillite. This middle belt lies between Maitlen phyllite on the southeast and Ordovician Ledbetter slate on the northwest, though on the Red Top Mountain extension it is flanked on the northwest by Cedar Creek argillite.

The northwest belt of Metaline limestone is exposed for several miles on both sides of the Columbia southwest from Northport, but only that part of it near Northport is shown on Plate 1.

STRATIGRAPHIC SECTIONS

General statement.—In its best exposure, on Gladstone Mountain, the Metaline limestone appears to be at least 6100 feet thick. Two shorter incomplete sections were measured also, one on each side of Deep Creek at the southwest end of the middle limestone belt.

Gladstone Mountain section.—The line of section is from upper Silver Creek west to Electric Point mine, thence northwest to Lead Trust mine.

	Thickness (feet)
Top concealed	
METALINE LIMESTONE	
Dolomite: massive, light gray	900+
Dolomite: thin-banded, medium gray	150
Dolomite: massive, light gray, and zones of breccia. Locally cherty	490
Dolomite: dark gray; thin white beds near top	50
Dolomite: massive, light gray	400
Dolomite: dark gray, locally oölitic, white-speckled; 2-inch to 6-foot light gray beds in increasing numbers downward; some irregular breccia areas	1300
Dolomite: massive, light gray; much of it cherty	1200+
Limestone and phyllite: gray, fine-grained, argillaceous limestone; phyllite beds near base	1600
Total thickness exposed of Metaline limestone	6090+

Lower Deep Creek section, east side.—The line of section is southeast between the two branches of the Nelson fault, and southeast from the Black Rock mine to the lowest beds.

	Thickness (feet)
METALINE LIMESTONE	
Nelson fault, northwest branch	
Limestone: medium gray, cherty	1000+
Nelson fault, southeast branch	
Limestone: thin streaky, white to medium gray	500+
Dolomite and limestone: white	400
Dolomite: interbedded dark and light gray beds 2 inches to 10 feet	250
Limestone and argillite: gray platy limestone and small lenses of gray argillite weathering olive	500
Dolomite: massive, white	350+
Total thickness exposed of Metaline limestone	3000+
Base eroded away	

Lower Deep Creek section, west side.—The line of section is southeast from the Stonewall thrust fault to the Occidental prospect; thence northeast to Deep Creek.

	Thickness (feet)
METALINE LIMESTONE	
Stonewall thrust fault	
Limestone: gray, cherty	1000+
Dolomite: white, massive, sugary	1500
Dolomite: interbedded light and medium gray	300
Dolomite: white, massive, sugary	600
Limestone: fissile, gray	100
Limestone: thin streaky, light and dark gray	650+
Total thickness exposed of Metaline limestone	4150+
Base covered	

LITHOLOGY AND INTERNAL STRUCTURE

In most areas of the Northport district, the upper third of the Metaline limestone is light-to medium-gray fine-grained calcite marble. The fine-grained dolomite of the Gladstone Mountain section is exceptional.

Chert is more common in the upper part of the formation than elsewhere, but cannot be safely used as a stratigraphic marker. It forms dull-gray, spherical to very irregular nodules, generally less than an inch in diameter. Veinlets connect some of the nodules. The chert probably is hydrothermal in origin, as fragments in a tectonic (?) breccia are coated with chert similar to that in the nodules.

Masses of black jasperoid and sugary gray dolomite have formed near some faults. Such alteration accompanied ore deposition in the Metaline quadrangle and was considered to be hydrothermal by Park and Cannon (1943, p. 44–45).

The massive light-gray dolomite in the middle third of the Metaline limestone is of a fairly uniform pearl-gray color and 0.1 mm. grain size. In the sections in the lower part of Deep Creek the dolomite is a white sugary marble of 0.5–1 mm. grain size. This white marble west of the creek contains several per cent of white tremolite in small prisms and as irregular veins and lenses. The tremolite is presumably a product of reaction of dolomite with solutions from the granitic batholith exposed to the southwest (Pl. 1).

The dark-gray and light-gray interbedded beds are of 0.05–0.1 mm. grain size and have the same mosaic texture. They contain irregular clouds of fine carbon particles. The dark-gray dolomite is finely speckled and streaked parallel to the bedding with nearly white dolomite flecks, the larger of which have a comb structure. The flecks may have formed during either dolomitization or ore deposition. Near the Gladstone mine, the dark dolomite consists of crowded black oölites less than 1 mm. in diameter.

In some shatter zones, the dark beds have been bleached almost to the color of the light ones within a transition zone of a few inches. The solutions that deposited galena near by probably also caused bleaching along the fracture cleavage elsewhere.

Three variants of the interbedded light and dark dolomites may indicate shearing between beds during folding. One variant was described by Park and Cannon (1943, p. 42–43) under the miners' term of "zebra" rock. The "zebra" banding occurs in

some of the dark-gray beds and consists of evenly spaced light- and dark-gray layers diagonal to the bedding planes. Park and Cannon (1943, p. 43) suggested that the light banding is due to recrystallization of the dark-gray dolomite along minute closely spaced cracks. This is probable, as such cracks would form in the brittle dolomite as a result of shearing between beds during folding. The system of cracks would thus be a kind of fracture cleavage and would offer passage to solutions capable of recrystallizing the dolomite. "Zebra" rock is common in the vicinity of the Iroquois mine, 3 to 4 miles northeast of Leadpoint, but is less common on Gladstone Mountain.

In the rare second variant of the interbedded light and dark dolomites, there are thin layers of flat ellipsoidal masses instead of continuous beds of dark-gray dolomite. The ellipsoids, 1 to 4 inches broad and generally less than an inch thick, consist of black cores surrounded by a fine mixture of white and black crystals. Between ellipsoids is the same light-gray dolomite that forms the flecks in the ordinary dark-gray type.

The third variant is a breccia composed of dark-gray tabular fragments of dolomite in a pale-buff coarse dolomite cement; some of the fragments are of "zebra" rock. Most of the fragments are less than 6 inches long and 2 inches thick; they lie roughly parallel to the bedding in some places and are unoriented in others. The smaller masses of breccia generally are parallel to the bedding, but the larger ones locally cut across it. These facts suggest that the breccia is tectonic instead of intraformational. However, as a breccia that apparently originated on tidal flats was described by Park and Cannon (1943, p. 22, Pl. 10), both types of breccia may be present.

The origin of the supposedly tectonic breccia is perplexing. The breccia was shattered at the Lead Trust mine during the reverse faulting that may have succeeded the folding. As the "zebra" rock was presumably formed during the folding, it follows that the breccia was formed and cemented sometime between an advanced stage of the folding and the reverse faulting. The breccia may be a product of the initial reverse faulting that began along the interbedded light and dark dolomites and caused the dark beds to break up while the light beds flowed around the fragments. What became of the original light-gray beds, or why most of the matrix of the breccia appears to be vein dolomite is not clear as it is unlikely that simple recrystallization effected the change.

The lower third of the Metaline limestone is distinctive in most areas. It consists of fine-grained platy gray limestone, much of which is either uniformly argillaceous or contains a network of veinlets and lumps of dark-gray argillaceous material that becomes olive brown and stands out on weathered surfaces.

Where the formation grades downward into the Maitlen phyllite are beds of limy gray and black phyllite, and the boundary is set at the horizon where limestone and phyllite beds are in approximately equal proportions (Park and Cannon, 1943, p. 16). Recent work by the U. S. Geological Survey indicates that phyllite beds do not occur in the basal part of the Metaline limestone in the type locality, but that the limestone is homogeneous and increasingly argillaceous downward; and the boundary with the Maitlen phyllite is now set at the horizon where calcite and argillaceous material are in equal volume (Vincent Nelson, oral communication, 1945). Well-defined slate

and phyllite beds alternate with limestone in the Northport district, and therefore the original criterion is used to establish the lower boundary of the Metaline limestone.

AGE AND CORRELATION

Two brachiopods, *Acrotreta* sp. and *Nisusia* sp., were found in the cherty light-gray dolomite about 2100 feet stratigraphically above the base of the Metaline limestone on Gladstone Mountain. They were recognized by Josiah Bridge (personal communication, October 31, 1942) as early Middle Cambrian, the same age as the trilobite collections from the lower part of the formation in the Metaline quadrangle. The brachiopod collection was made in 1942 from the NE.¼, NW.¼, Sec. 18, T.39 N., R.42 E., W.M., or 600 feet N.10° E. of the midpoint tower of the Electric Point aerial tram. Fossils have not been found in the upper half of the Metaline limestone, except for the unidentified trilobite in the Pend Oreille mine (Table 2), but there is no reason to think that the entire formation is not Middle Cambrian.

Small reefs of calcareous algae were found in gray limestone of the lower part of the Metaline limestone at the head of Todd Creek (Pl. 1). These were identified by Reeside (personal communication, January 13, 1945) as "the supposed alga, *Girvanella*," which occurs in many zones of Paleozoic rocks. No opinion was expressed by Reeside (personal communication, November 24, 1944) about similar nodular masses from the same stratigraphic horizon, 1½ miles northeast of the Electric Point mine.

As no other Cambrian fossils were found in the Northport district, correlations with the Metaline limestone had to be made on the basis of lithologic succession. The criteria used for correlation are discussed below. The first criterion, which can be used where the upper beds of the limestone are exposed, is the occurrence of Ledbetter slate stratigraphically above them. The second criterion can be used to recognize the lower part of the Metaline limestone, as it grades downward into a thick phyllite series. The third criterion is the lithologic sequence within the Metaline limestone itself:

TOP: Limestone or dolomite, especially if cherty.
MIDDLE: Light-gray dolomite and interbedded light and dark-gray dolomite.
BOTTOM: Gray limestone and phyllite beds.

The Old Dominion limestone of Weaver (1920, p. 66–68) in the Colville and Chewelah areas is believed by Bennett (personal communication, April 27, 1944) and the writer to be partly equivalent to the Metaline limestone, as the Old Dominion, like the Metaline, is overlain by Ordovician black argillite (Bennett, 1944, p. 9). However, the two limestones are not of exactly the same age, as the base of the Old Dominion is Lower Cambrian (Bennett, 1941, p. 9), and the base of the Metaline limestone is Middle Cambrian (Park and Cannon, 1943, p. 19).

MAITLEN PHYLLITE

DISTRIBUTION

Most of the Maitlen phyllite in the map area (Pl. 1) crops out in a strip about 5 miles long and 1 to 2 miles wide, which trends northeast from the batholith to Lead-

point. Only a small part of the formation along the east boundary of the Northport district was mapped, but it is reported to be continuous from the Russian Creek fault south to the batholith (Park and Cannon, 1943, Pl. 1).

A large area of Weaver's Cedar Creek argillite, which may be Maitlen phyllite, forms most of Red Top Mountain and extends to the slopes west of Cedar Lake.

Near Northport, the upper beds of the Maitlen phyllite are exposed in a few small areas where they dip beneath the Metaline limestone. Most of the Maitlen near Northport is buried under the alluvium of Deep Creek Valley.

STRATIGRAPHIC SECTIONS

General statement.—The entire thickness of the Maitlen phyllite is not exposed in any one place. The formation appears to be 3700 feet thick on Sherlock Creek 1½ miles northwest of Deep Lake (Pl. 1), but an unknown thickness of beds is believed to be concealed northwest of each of two strike faults that are probably branches of the Russian Creek fault.

No other section of proved Maitlen phyllite was measured. Two sections of Cedar Creek argillite were measured, but as the correlation of the Cedar Creek argillite with the Maitlen phyllite is in doubt, these sections are described later.

Sherlock Creek section.—The line of the section is across the mouth of Sherlock Creek, from the Gypsy quartzite contact 400 yards to the south, northward at valley level to the creek, thence northwest to the top of the ridge.

	Thickness (feet)
METALINE LIMESTONE	
Platy gray limestone	
Strike fault: northwest branch of Russian Creek fault	
MAITLEN PHYLLITE	
Phyllite: silvery gray	270
Slate: black	350
Sill: dark gray, aphanitic, biotite phenocrysts	300
Phillites: gray and green, containing 6 dark-gray aphanitic sills aggregating 310 feet in thickness	2360
Strike fault: southeast branch of Russian Creek fault, believed to pass through the lower part of the gray and green phyllites	
Sill: dark gray, aphanitic	200
Phyllite: black, containing 1 dark-gray aphanitic sill 30 feet thick	360
Phyllite; green	120
Sill: dark gray, aphanitic	30
Limestone: gray and white	290
Phyllite: green	260
Total thickness exposed of Maitlen phyllite	3670
Thickness of included sills	870
Total thickness of section	4540

LITHOLOGY AND INTERNAL STRUCTURE OF MAITLEN PHYLLITE

A considerable variety of schists, phyllites, and slates form the main body of the Maitlen phyllite and differ from each other mainly in texture and in their proportions

of quartz, muscovite, and slightly chloritized biotite. One quartz-muscovite phyllite in the Sherlock Creek area contains 5 per cent of ottrelite porphyroblasts.

The limestone bed near the base of the formation was first recognized in the Metaline quadrangle (Park and Cannon, 1943, p. 15–16), where it is 200 feet thick and lies 100 feet above the Gypsy quartzite. South of Sherlock Creek, this bed is 290 feet thick and consists of both gray and white limestones or fine-grained marbles.

In nearly every outcrop of phyllite examined, the schistosity parallels the bedding. The cleavage surfaces are finely wrinkled in many places, so that the positions of the axes of the larger folds can be determined. Elsewhere, fracture cleavage serves the same purpose.

A quartzite of unknown thickness occurs in an area of poor exposures of Maitlen phyllite a mile west of Deep Lake.

AGE AND CORRELATION

Fossils have not been found in the Maitlen phyllite. The Metaline limestone, which overlies it, is of Middle Cambrian age, and the Gypsy quartzite, which underlies it, contains Lower or Middle Cambrian fossils (Table 2); hence, the Maitlen phyllite is either Lower Cambrian or Middle Cambrian.

Correlation of the phyllites in most of the Northport district was made almost entirely on a lithologic basis. Near the head of Silver Creek, however, the phyllite is continuous from the Metaline to the Colville quadrangles, and correlation was certain.

The criterion for recognizing the upper part of the Maitlen phyllite is the gradational limestone-phyllite zone which passes upward into the Metaline limestone. The lower part of the Maitlen phyllite is easily recognized by the presence of the gray and white limestone bed, 200 to 300 feet thick, which lies 100 to 300 feet above the Gypsy quartzite.

GYPSY QUARTZITE

DISTRIBUTION

The Gypsy quartzite is exposed over about a square mile, a short distance northwest of Deep Lake. Except for a normal contact with the Maitlen phyllite to the northwest, the quartzite is surrounded by down-faulted blocks.

THICKNESS AND LITHOLOGY

Of a total thickness of 5335 feet measured above the Oriole mine in the Metaline quadrangle (Park and Cannon, 1943, p. 13–15), only the upper 2500 feet of the Gypsy quartzite is visible.

Near the top of the Deep Lake section are alternate beds of quartzite and mica schist or phyllite, each a few feet thick, with fewer thin beds of yellowish-white marble. Below this succession is a thick mass of feldspathic quartzite. The rest of the exposure consists of gray-green quartzite and phyllite cut by quartz veins and basic sills.

AGE AND CORRELATION

Fossils were not seen in the Gypsy quartzite of the Northport district. The upper zone of alternate quartzite and phyllite beds in the Metaline quadrangle contains "burrows," or fucoidal cylinders, and "crooked rods of organic (?) origin" (Park and Cannon, 1943, p. 13–14). Such markings were not seen in the quartzites northwest of Deep Lake. The upper part of the Gypsy quartzite in the northeast part of the Metaline quadrangle (Park and Cannon, 1943, p. 15) contains poorly preserved Cambrian trilobites (Table 2).

The basis for correlating the quartzite-phyllite series near Deep Lake with the Gypsy quartzite in the type area is lithologic succession. In both areas the "200 foot bed" of limestone near the base of the Maitlen phyllite is underlain by a phyllite bed, below which are the interbedded quartzites and phyllites of the top of the Gypsy quartzite.

Bennett (personal communication, April 27, 1944) considers that the Gypsy quartzite probably is correlative with the Addy quartzite (Weaver, 1920, p. 61–63) in the Colville-Chewelah area. Bennett (1944, p. 31) reports trilobite fragments and brachiopods about 1500 feet below the top of the Addy quartzite (5000 feet). These fossils must be Lower Cambrian, as the base of the overlying Old Dominion limestone contains Lower Cambrian brachiopods (Branson, 1931).

CEDAR CREEK ARGILLITE

DISTRIBUTION

The Cedar Creek argillite was named by Weaver (1920, p. 80–81) for its occurrence on Red Top Mountain within the horseshoe formed by Cedar Creek and its East Fork (Pl. 1). He also mapped the formation north and northeast of Cedar Creek to the International Boundary. Only the former occurrence was examined during the present work.

A series of rocks closely similar to the type Cedar Creek argillite crops out west of Cedar Lake, from O'Hare Creek north to the edge of a granodiorite stock. These rocks are part of the Boundary argillite of Weaver (1920, p. 81), but appear to be an extension of the Cedar Creek argillite. The Melrose mine, about 2½ miles west of Cedar Lake (Pl. 1), is in dark-gray phyllite similar to that in the lower part of the Cedar Creek argillite east of the lake.

STRATIGRAPHIC SECTIONS

General statement.—The least-disturbed section of the Cedar Creek argillite is the Red Top Mountain section, which is fairly well exposed on the east half of the mountain. At both ends of a gap in the section are exposures of quartzite, which are assumed to be parts of one unit of quartzite 450 feet thick. The entire thickness of this unit can be seen near the Cedar Lake road, in the line of the Cedar Lake section.

Red Top Mountain section.—The line of the section is southeast across the Red Top mine, from the Copper King workings to the main tunnel, thence offset along strike half a mile northeast to the Lucile mine, thence southeast across a short section at the Lucile mine. Exposures resumed 3000 feet to the northeast, at valley level, thence northwest 1½ miles to the north base of the mountain.

	THICKNESS (feet)
RED TOP LIMESTONE	
Limestone: light gray, banded, with at least 1 bed of quartz-mica schist	
CEDAR CREEK ARGILLITE	
Argillite and slate: black	300
Phyllite and quartzite: silvery green, and many beds of quartzite $\frac{1}{16}$ to $\frac{1}{4}$ inch thick	110
Marble: light gray and white, fine-grained, thin-bedded	220
Phyllite- silvery green	130
Marble: creamy white, medium-grained, siliceous	90
Quartzite: red brown, fine-grained, micaceous	140+
Gap in section (assumed thickness)	160
Quartzite and slate: gray-green micaceous quartzite, and a few beds of black slate	150+
Marble: light gray, fine-grained, thin-banded	400
Phyllite: dark gray	100
Phyllite: silvery green	500
Phyllite: greenish gray-black	700+
Total thickness exposed of Cedar Creek argillite	2840

Base is covered.

A second section of the same beds is exposed along the Cedar Lake road at the west base of Red Top Mountain. Because these rocks are disturbed by faults and overturned folds, and because exposures are limited, their succession would be virtually impossible to decipher if the Red Top Mountain section were not known.

Cedar Lake section.—The following section shows the range in thickness and lithologic changes of the rocks in the $1\frac{1}{2}$ to 2 miles between the two lines of section. The line of the Cedar Lake section extends along the road north of Leadpoint, from Hartbauer Creek northward to the last outcrops, about a mile north of Cedar Lake.

	THICKNESS (feet)
RED TOP LIMESTONE	
Limestone: gray, thin-bedded	
CEDAR CREEK ARGILLITE	
Covered unit	
Phyllite: black	50+
Phyllite: silvery gray	120
Phyllite and quartzite: silvery green phyllite, and many beds of quartzite $\frac{1}{16}$ to $\frac{1}{4}$ inch thick	290
Phyllite and quartzite: biotite phyllite, and quartzite beds in upper part	300
Marble: white, massive, sugary	100
Schist: chlorite	35
Marble: white, massive, sugary	100
Quartzite: micaceous, locally calcareous	450
Marble: yellow white, sugary	400+
Covered unit	115
Phyllites and limestone: gray and green phyllites, and a few beds of limestone about an inch thick	285+
Phyllite: black, with small pyrite cubes	200+
Total thickness exposed of Cedar Creek argillite	2445

Base covered.

AGE AND CORRELATION

Fossils have not been found in the Cedar Creek argillite. Because this formation does not entirely resemble any in the Metaline quadrangle, its stratigraphic position is uncertain. The Cedar Creek argillite may be a formation not recognized in the Metaline quadrangle. If so, it would most probably be the upper part of the (Ordovician) Ledbetter slate, and the overlying Red Top limestone would be correlative with the Devonian limestone of the Metaline quadrangle (Park and Cannon, 1943, p. 22–23).

More probably the Cedar Creek argillite is correlative with the Maitlen phyllite, and the Red Top limestone with the Metaline limestone, for the phyllite and limestone series are in gradational contact in both the Northport and Metaline areas The quartzite unit 450 feet thick, which occurs 850 to 1000 feet below the top of the Cedar Creek argillite, has not been reported from the Maitlen phyllite of the Metaline quadrangle. It does occur in the upper part of the Maitlen phyllite a mile west of Deep Lake.

CONCLUSIONS

The remapping of northeastern Stevens County and the discovery of Cambrian and Ordovician fossils in that area are thought to justify the adoption there of formation names established by Park and Cannon (1943) for the Metaline quadrangle. The new names replace those given by Weaver (1920). The principal changes are indicated below.

Correlative with the Middle Cambrian Metaline limestone are most of Weaver's Northport limestone, Republican Creek limestone, Red Top limestone, and Deep Lake argillite, and part of the Boundary argillite.

Correlative with the Maitlen phyllite are parts of Weaver's Northport limestone, Boundary argillite, Deep Lake argillite, and all of the Cedar Creek argillite.

Correlative with the Gypsy quartzite is a small part of the Boundary argillite.

STRUCTURAL SETTING

Cambrian and Ordovician formations of the Northport district lie in long folds trending northeast. Axial planes of folds and the soles of reverse faults dip southeast at moderate angles.

A granitic batholith, which is probably Upper Cretaceous (Park and Cannon, 1943, p. 26), its satellitic stocks, and its swarms of lamprophyre dikes cut the folds discordantly.

The older sedimentary rocks of the Summit series and Priest River Terrane (Daly, 1912, p. 141–159, 258–271), aggregating 35,000 to 40,000 feet in thickness, are believed to underlie the district if they have not been stoped out by the batholith. From 4 to 5 miles northwest of Columbia River, the rocks of the Northport district pass beneath the Rossland volcanic group, of Mesozoic to possibly Miocene age (Weaver, 1920, p. 93–95).

The areal map (Pl. 1) shows the major high-angle faults but does not suggest the

multitude of small faults and areas of shattering. This faulting probably took place sometime after the intrusion of the granitic rocks and continued for some time while ore deposits of the district were formed.

REFERENCES CITED

Bancroft, Howland (1914) *The ore deposits of northeastern Washington*, U. S. Geol. Survey, Bull. 550, p. 1–215.

Bennett, W. A. G. (1941) *Preliminary report on magnesite deposits of Stevens County, Washington*, Wash. Dept. Cons. Devel., Div. Geol., Rept. Invest. 5, p. 1–25.

———(1944) *Dolomite resources of Washington*, Wash. Dept. Cons. Devel., Div. Geol., Rept. Invest. 13, p. 1–35.

Branson, C. C. (1931) *New paleontologic evidence on the age of the metamorphic series of northeastern Washington*, Science, n. s., vol. 74, p. 70.

Culver, H. E. (1936) *The geology of Washington, Part I, General features of Washington geology*, Wash. Dept. Cons. Devel., Div. Geol., Bull. 32, p. 1–70.

Daly, R. A. (1912) *Geology of the North American Cordillera at the Forty-Ninth Parallel*, Canada Dept. Mines, Geol. Survey, Mem. 38, p. 1–857.

Howell, B. F. (1945) *Fauna of Cambrian Metaline formation of Washington* (Abstract), Geol. Soc. Am., Bull., vol. 56, p. 1169.

Jenkins, O. P. (1924) *Lead deposits of Pend Oreille and Stevens Counties, Washington*, Wash. Dept. Cons. Devel., Div. Geol., Bull. 31, p. 1–153.

Jones, R. H. B. (1928) *The geology of the Chewelah quadrangle, Stevens County, Washington*, Northwest Science (Spokane), vol. 2, p. 111–116.

Park, C. F., Jr. (1938) *Dolomite and jasperoid in the Metaline district, northeastern Washington*, Econ. Geol., vol. 33, p. 709–729.

——— and Cannon R. S., Jr. (1943) *Geology and ore deposits of the Metaline quadrangle, Washington*, U. S. Geol. Survey, Prof. Paper 202, p.1–81.

Patty, E. N. (1921) *The metal mines of Washington*, Wash. Geol. Survey, Bull. 23, p. 1–366.

Resser, C. E. (1934) *Recent discoveries of Cambrian beds in the Northwestern United States*, Smithson. Misc. Coll., vol. 92, no. 10, p. 1–10.

Walker J. F. (1934) *Geology and mineral deposits of Salmo Map-Area, British Columbia*, Canada Dept. Mines, Geol. Survey, Mem. 172, p. 1–102.

Weaver C. E. (1920) *The mineral resources of Stevens County*, Wash. Geol. Survey, Bull. 20, p. 1–320.

Harvey Road, Pullman, Washington

Manuscript Received by the Secretary of the Society, June 17, 1946

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 58, PP. 613-688, 6 FIGS. JULY 1947

HOLARCTIC MAMMALIAN FAUNAS AND CONTINENTAL RELATIONSHIPS DURING THE CENOZOIC

BY GEORGE GAYLORD SIMPSON

CONTENTS

	Page
Abstract	614
Introduction	614
Some basic data on migration	617
Times of migrations	622
Directions of migrations	628
Taxonomy of migrants and nonmigrants	632
General considerations	632
Early Eocene	632
Middle Eocene	633
Late Eocene	634
Early Oligocene	635
Middle and Late Oligocene	637
Early and Middle Miocene	638
Late Miocene	639
Early Pliocene	640
Middle Pliocene	641
Late Pliocene	642
Pleistocene	642
General summary	644
Selectivity of migration	645
Times of intercontinental connections	654
General considerations	654
Paleocene	655
Eocene	655
Oligocene	655
Miocene	656
Pliocene	656
Pleistocene	657
Places of intercontinental connections	657
Faunal resemblance	671
Summary	685
References cited	686

ILLUSTRATIONS

Figures	Page
1.—Items of evidence of migration of land mammals between Eurasia and North America, ferungulates only	625
2.—Absolute numbers of known genera and families of nonvolant land mammals peculiar to Eurasia or North America and common to both	674
3.—Taxonomic resemblance between known Eurasian and North American nonvolant land mammals	681

4.—Migration curve and generic resemblance curve superposed 682
5.—Theoretical and generalized diagram of the interplay of factors making for greater faunal resemblance and those making for less during one simple cycle of faunal interchange, with resultant changes in taxonomic resemblance between two areas involved in the interchange 684
6.—Theoretical and generalized diagram of interplay of factors making for more or less faunal resemblance between two regions, one of which also interchanges faunal elements with a third region, while the two regions are continually or continuously connected by a migration route 684

ABSTRACT

A series of tables lists land mammals common to North America and Eurasia, their probable times of migration by subepochs throughout the Cenozoic, and important groups that did not migrate in given subepochs. Major faunal interchanges occurred in early Eocene, late Eocene, early Oligocene, late Miocene, middle to late Pliocene, and Pleistocene. There was little or no interchange in the middle Eocene and middle to late Oligocene. Each interchange involved migration in both directions, but there was probably more movement from Eurasia to North America than in the opposite direction. All interchanges were selective, and they became increasingly limited from Eocene to Pleistocene. The most important selective influence was probably the relatively cold climate of the land connection. This connection was probably from Siberia to Alaska throughout the Cenozoic and was in almost continuous existence with important interruptions in parts of the Eocene and Oligocene and perhaps shorter interruptions at later times. The measurement of faunal resemblance in general is discussed, and mammalian faunal resemblance between Eurasia and North America charted for the Cenozoic. Changes in resemblance are correlated with five factors: faunal interchange, extinction of autochthones, divergent evolution, local extinction of migrants, and migration from other regions.

INTRODUCTION

The earliest European explorers of North America did not fail to notice that some among the animals encountered here were almost identical with those known to them in the Old World, while others were quite different and characteristic of the New World. Eighteenth century zoologists had already concluded that the faunal resemblances of the eastern and western hemispheres suggested a former connection between the continents. They had also begun to speculate on the reasons for the differences between Old and New World faunas. It is now remembered with some amusement that Buffon held that the humidity of the New World had stunted animal growth there and that animals common to America and Europe reached their full development only on the latter continent. As a patriotic American, Thomas Jefferson demolished this theory by remarking at great length and with complete justice that it was not known that America is more humid, that humidity would be more likely to promote than to inhibit growth, and that American animals are not really smaller than European, anyway.

Early discoveries of fossils added data for enquiry and fuel for controversy. The first real identification of an American fossil was made, sometime before 1740, by African slaves who recognized some fossil teeth as being those of elephants, similar to the African species. Around the end of the eighteenth century there was much discussion as to the relationships between the Siberian and American mammoths.

These early students had, however, little conception of the implications involved in such zoological and geographical relationships. (*See* Simpson, 1942.)

During the nineteenth century geologists demonstrated the instability of continental shorelines and worked out many of the details in the recurrent flooding and emersion of large parts of the continents. The paleontologists found numerous land faunas of different ages, and by the end of the nineteenth century the main features of the Tertiary mammalian sequence were known for North America and Europe. It then became clear that the degree and nature of faunal resemblance between different continents, changing throughout geological time, is related to the appearance and disappearance of practicable migration routes. The Sclaters (1899) and Lydekker (1896) treated mammalian zoogeography as a historical subject and against this background. Using the data of numerous paleontologists, they noted that the early Tertiary mammals of North America and Eurasia were closely similar and that the similarity became less later in the Tertiary and finally greater again toward and after the end of that period. The Sclaters took this as an indication that North America and Eurasia (also Africa) were one land mass until North America broke away in the Tertiary, with a limited Siberia-Alaska bridge appearing in the late Tertiary. Lydekker supposed that this bridge existed almost if not quite continuously during the Tertiary, but that it was so narrow and northern that the more southerly animals of the two hemispheres could become increasingly divergent.

Paleomammalogists were long and intensely concerned with filling in the details of the over-simplified picture presented by Lydekker and the Sclaters. Early in the twentieth century their efforts culminated in more or less parallel studies by the then leading students of this subject in Europe and in North America: Depéret (1905; 1906a; 1906b, 1907) and Osborn (1910). They presented a great wealth of information and followed the Eurasian-North American faunal relationships throughout the Tertiary.

Since Osborn's *The age of mammals in Europe, Asia, and North America* (1910), no review of this subject comparable in scope and detail has appeared. The subject has not been neglected; on the contrary, its bibliography has grown inordinately during this period. It is, for instance, treated at length in Arldt's massive *Handbuch der Palaeogeographie* (1919–1922), but knowledge was not appreciably advanced by Arldt's compilation. On given points, it is no easy matter to find the pertinent passages in this work, and, when they are found, the judicious student will observe that the data are unreliable and are mingled with baseless speculations, not invariably labeled as such. The accounts that appear incidentally in most texts of historical geology, although often clearer and sounder than Arldt, are derivative and commonly stem essentially from Osborn's work of 1910. Some later works on paleogeography (notably that by Furon, 1941), although incorporating some more recent discoveries, are really far less up-to-date than the work of Depéret and of Osborn a generation earlier.

Discussion of the hypothesis of continental drift has also involved many references to faunal relationships between Eurasia and North America, but, as I have pointed out elsewhere (Simpson, 1943), most of the references in this literature to this subject are extremely unreliable or otherwise misleading.

Most of the original and sound work on this topic is scattered in innumerable papers

each treating only a limited part of the problem. Thus descriptions of individual fossils may point out an intercontinental relationship exemplified by that fossil. For example, Burke (1936) reports the presence of two Asiatic genera in the North American Oligocene but does not discuss the migration involved. Faunal revisions may include a more general consideration of the relationships at one particular time. For example, Scott and Jepsen (1936) discussed the Asiatic-North American Oligocene connection, without going into any considerable detail about it. Interest in early man has stimulated extensive studies of Pleistocene migrations. For example, Colbert (1937) considered this problem briefly but rather thoroughly in a symposium on early man.

In spite of all this work of summary and of detail, there has been no good source later than 1910 to which a student could be referred for an adequate but general discussion of the relationships of the Eurasian and North American mammalian faunas throughout the Cenozoic. The problems and questions involved are legion, and they are of crucial importance not only to paleomammalogists, who might be expected to answer their own questions, but also to neomammalogists, ornithologists[1], zoologists in general, botanists, geologists, climatologists, and many others, including a considerable number of interested nonscientists.

Failure to supply this strongly felt need for some years after 1910 was undoubtedly due to the feeling that, "It is all in Osborn's *Age of mammals*." As that classic inevitably went out of date, no one was inspired to revise or emulate it because of the enormous labor involved and because of well-founded suspicion that no amount of labor would provide complete or final answers to any of these questions.[2]

It is, indeed, true that full understanding of the history of Eurasian-North American mammalian faunal relationships is now unattainable. It is, nevertheless, possible to prepare a sort of interim report, and that is the purpose of the present paper. It would be of relatively little value simply to tabulate or summarize the data without also attempting to interpret them. Such interpretation is here attempted, with full realization that many points still rest on an insecure basis and are open to radical emendation as a result of future study.

This paper is based on and confined to mammals. The inferences and interpretations here reached are therefore applicable primarily and in some respects only to the mammalian faunas. Insofar as these results may be correct, they will be consistent with the history of other groups of organisms in the same region, but they may nevertheless prove to be quite different. Each different group of organisms has its own ecological and distributional characteristics and processes and therefore may have its own distinctive history although all have evolved within the same framework, geologic, geographic, climatic, etc.[3]

Another general caution is necessary regarding the use of the word "migration."

---

[1] The present study, which has far outgrown its original scope, started as an attempt to answer the following questions submitted to me by an ornithologist, Ernst Mayr: During what times in the Tertiary was a migration route between Eurasia and North America open? How long did it exist in each case? What faunal elements moved from east to west and what others from west to east? What was the climate of the bridge during each of the various times when it was open?

[2] It is of interest that Osborn, himself, planned to revise *The age of mammals* and went on accumulating an immense body of data for this purpose up to the time of his death. A lifetime would hardly now suffice to perform the task on the scale that he apparently anticipated, and the resultant mass of detail might obscure as much as it illuminated.

[3] *See*, for example, Mayr (1946) for an interpretation of the history of the North American bird fauna which is consistent with but different from the history of the North American mammalian fauna.

Throughout this paper (unless especially qualified), "migration" is used to mean the spread of a mammalian group from one continent to another. There is abundant precedent for this convenient usage, but migration in this sense is quite different from the annual migration of birds or the occasional migration of lemmings, for instance. In most cases it is probable that the intercontinental migrations here considered did not involve any movement of populations as a whole or as such, but only their peripheral expansion. (The distinction between the two senses of migration is clarified and emphasized in Mayr, 1941.)

After this paper was complete in first draft, it was submitted to a number of colleagues, and I am particularly indebted to the following for constructive criticisms: Edwin H. Colbert, Ernst Mayr, Paul O. McGrew, Norman D. Newell, Bryan Patterson, R. A. Stirton, Albert E. Wood, and Horace E. Wood, 2nd. The much appreciated co-operation of these authorities has enabled me to clarify many points and to avoid many errors. Of course the paper as it stands is not integrally endorsed by any one of these colleagues, and they are not responsible for remaining obscurities or errors of fact or judgment.

SOME BASIC DATA ON MIGRATION

Essential data bearing on intercontinental migration are dated records of taxonomic groups common to the two continents. From these the times of common occurrence of particular groups and the fluctuations in faunal resemblance are observed. Similar records of groups confined to one continent or another are equally necessary and may be scarcely less enlightening. For the problems of the directions and times of migration, and hence of the natures and the times of existence of migration routes, the most pertinent data are the times and places of first occurrence of groups common to the two areas and the (frequently somewhat later) times when they became common to the two. The present enquiry begins with these data, some of which are presented in Table 1.

This table lists first known occurrence in each area of families, subfamilies, and genera of Tertiary and Quaternary land mammals known to be common to Eurasia and North America. The classification and distribution records are taken, with some emendation, from Simpson (1945). Use, for this purpose, of taxonomic groups higher than families has little value because the categories are too broad. Categories below the genus are too narrow; very few are recorded as common to the two land masses in question. The useful categories thus range from family to genus, and the consideration of both of these is necessary because, as will appear later, they have somewhat different implications and reveal different parts of the picture. In the classification here followed, not all families are divided into subfamilies, but this category is listed because it occasionally adds some pertinent data. Europe and Asia are listed as separate units, although in much of the subsequent discussion Eurasia will be considered as a single continent. Distribution within that land mass on which the data are very incomplete, has an important bearing on some of the problems under consideration and will be discussed, in part, in a later section. Marine mammals and bats are omitted, because they are subject to quite different distributional factors and because, particularly in the case of the bats, the fossil record is extremely inadequate. As emphasized elsewhere, intercontinental cor-

TABLE 1.—*Times of appearance of mammals common to Eurasia and North America*

Abbreviations:

As., Asia	U., upper or late	Mioc., Miocene
Eu., Europe	Cret., Cretaceous	Plioc., Pliocene
N. A., North America	Paleoc., Paleocene	Pleist., Pleistocene
L., lower or early	Eoc., Eocene	R., Recent
M., middle	Olig., Oligocene	

	Earliest known occurrence	Earliest known occurrence elsewhere in Eurasia or North America
Ptilodontidae	U. Cret.; N. A., As.	U. Paleoc.; Eu.
Ptilodontinae	U. Cret.; N. A.	U. Paleoc.; Eu.
Ectypodus	?M., U. Paleoc.; N. A.	U. Paleoc.; ?Eu.
Didelphidae	U. Cret.; N. A.	?U. Paleoc., Eoc.; Eu.
Didelphinae	L. Paleoc.; N. A.	?U. Paleoc., Eoc.; Eu.
Peratherium	L. Eoc.; N. A.	?U. Eoc.; Eu.
Deltatheridiidae	U. Cret.; As.	L. Paleoc.; N. A.
Leptictidae	U. Cret.; N. A.	U. Paleoc.; Eu.
Erinaceidae	L. Eoc.; N. A.	U. Eoc.; Eu. Olig.; As.
Echinosoricinae	L. Eoc.; N. A.	U. Eoc.; Eu. R.; As.
Meterix	L. Plioc.; N. A.	U. Mioc.; ?Eu.
Erinaceinae	Olig.; Eu., As.	U. Mioc.; ?N. A.
Nyctitheriidae	M. Paleoc.; N. A.	L. Eoc.; Eu.
Soricidae	U. Eoc.; Eu.	L. Olig.; N. A. L. Mioc.; As.
Soricinae	U. Eoc.; Eu.	L. Olig.; N. A. L. Plioc.; As.
Sorex	L. Mioc.; Eu.	U. Plioc.; N. A. Pleist.; As.
Crocidurinae	U. Mioc.; Eu., N. A.	L. Plioc.; As.
Talpidae	U. Eoc.; Eu.	U. Olig.; N. A. Pleist.; As.
Talpinae	U. Eoc.; Eu.	?M.-U. Mioc.; ?N. A. R.; As.
Scalopinae	U. Olig.; N. A.	M. Mioc.; ?Eu. R.; As.
Pantolestidae	M. Paleoc.; N. A.	L. Eoc.; Eu.
Pantolestinae	M. Paleoc.; N. A.	L. Eoc.; Eu.
Palaeosinopa	L. Eoc.; N. A., Eu.	
Plesiadapidae	M. Paleoc.; N. A.	U. Paleoc.; Eu.
Plesiadapis	U. Paleoc.; N. A., Eu.	
Adapidae	L. Eoc.; N. A., Eu.	
Notharctinae	L. Eoc.; N. A., Eu.	
Anaptomorphidae	M. Paleoc.; N. A.	L. Eoc.; Eu. Olig.; ?As.
Omomyinae	U. Paleoc.; N. A.	L. Eoc.; Eu.
Apatemyidae	M. Paleoc.; N. A.	L. Eoc.; Eu.
Hominidae	L. Pleist.; Eu., As.	U. Pleist.; N. A.
Homo	M. Pleist.; Eu., As.	U. Pleist.; N. A.
Tillotheriidae	U. Paleoc.; N. A.	L. Eoc.; Eu.
Esthonyx	U. Paleoc.; N. A.	L. Eoc.; Eu.
Stylinodontidae	L. Paleoc.; N. A.	L. Eoc.; Eu.
Ectoganus	L. Eoc.; N. A., Eu.	
Ochotonidae	L. Olig.; N. A.	Olig.; Eu., As.
Desmatolagus	L. Olig.; ?N. A.	Olig.; As.
Ochotona	U. Mioc.; Eu., As.	Pleist.; N. A.
Leporidae	U. Eoc.; N. A., As.	Olig.; Eu.
Palaeolaginae	U. Eoc.; N. A., As.	?Olig., Plioc.; Eu.
Hypolagus	M. Mioc.; N. A.	U. Plioc.; Eu., As.
Alilepus	Mioc.; ?Eu.	Plioc.; As., ?N. A.
Leporinae	Plioc.; Eu., As.	?Plioc., Pleist.; N. A.
Lepus	Pleist.; Eu., As., N. A.	

TABLE 1—*Continued*

	Earliest known occurrence	Earliest known occurrence elsewhere in Eurasia or North America
Ischyromyidae	U. Paleoc.; N. A.	L. Eoc.; Eu. Olig.; As.
Paramyinae	U. Paleoc.; N. A.	L. Eoc.; ?Eu.
Sciuravinae	M. Eoc.; N. A.	U. Olig.; As.
Prosciurus	L. Olig.; N. A.	U. Olig.; As.
Cylindrodontinae	L. Eoc.; N. A.	L. Olig.; As.
Ardynomys	L. Olig.; N. A., As.	
Aplodontidae	U. Eoc.; N. A.	L. Plioc., As.
Eomyidae	U. Eoc.; N. A., Eu.	
Sciuridae	U. Mioc.; N. A., Eu.	Pleist.; As.
Sciurinae	U. Mioc.; N. A., Eu.	Pleist.; As.
Sciurus	Pleist.; N. A., Eu., As.	
Marmota	M. Plioc.; N. A.	Pleist.; Eu., As.
Citellus	U. Mioc.; N. A.	U. Plioc.; As. Pleist.; Eu.
Tamias	U. Mioc.; N. A.	Pleist.; Eu., As.
Petauristinae	Pleist.; N. A., Eu., As.	
Petaurista	Pleist.; N. A., As.	
Castoridae	L. Olig.; N. A.	U. Olig.; Eu. U. Mioc.; As.
Castorinae	L. Olig.; N. A.	U. Mioc.; Eu. L. Plioc.; As.
Castor	Plioc.; N. A., Eu., As.	
Castoroidinae	U. Olig.; Eu.	L. Mioc.; N. A., As.
Monosaulax	M. Mioc.; N. A., ?Eu.	
Dipoides	M. Plioc.; N. A., Eu., As.	
Amblycastor	U. Mioc.; N. A., As.	
Cricetidae	L. Olig.; Eu., As.	M. Olig.; N. A.
Cricetinae	L. Olig.; Eu.	M. Olig.; N. A. U. Olig.; As.
Eumys	M. Olig.; N. A.	U. Olig.; As.
Cricetodon	L. Olig.; Eu., ?As.	M. Olig.; N. A.
Microtinae	U. Mioc.; N. A.	M. Plioc.; Eu., As.
Dicrostonyx	Pleist.; Eu., As.	R.; N. A.
Lemmus	Pleist.; Eu.	R.; N. A., As.
Clethrionomys	Pleist.; Eu., N. A., As.	
Mimomys	U. Plioc.; Eu., N. A.	Pleist.; As.
Pitymys	Pleist.; N. A., Eu., As.	
Microtus	Pleist.; N. A., Eu., As.	
Lagurus	U. Plioc.; Eu.	Pleist.; As. R.; N. A.
Zapodidae	Olig.; Eu.	L. Plioc.; As. M. Plioc.; N. A.
Zapodinae	M. Plioc.; N. A.	R.; As.
Zapus	Pleist.; N. A.	R.; As.
Arctocyonidae	L. Paleoc.; N. A.	U. Paleoc.; Eu., ?As.
Oxyclaeninae	L. Paleoc., N. A.	U. Paleoc.; Eu.
Arctocyoninae	M. Paleoc.; N. A.	U. Paleoc.; Eu.
Mesonychidae	M. Paleoc.; N. A.	U. Paleoc.; Eu. U. Eoc.; As.
Dissacus	M. Paleoc.; N. A.	U. Paleoc.; Eu.
Hapalodectes	L. Eoc.; N. A.	U. Eoc.; ?As.
Pachyaena	L. Eoc.; N. A., Eu.	
Oxyaenidae	U. Paleoc.; N. A.	L. Eoc.; Eu. U. Eoc.; As.
Oxyaeninae	U. Paleoc.; N. A.	U. Eoc.; As.
Palaeonictinae	U. Paleoc.; N. A.	L. Eoc.; Eu.
Palaeonictis	L. Eoc.; Eu., N. A.	

TABLE 1—*Continued*

	Earliest known occurrence	Earliest known occurrence elsewhere in Eurasia or North America
Hyaenodontidae	L. Eoc.; N. A., Eu.	U. Eoc.; As.
Proviverrinae	L. Eoc.; N. A., Eu.	U. Eoc.; As.
Sinopa	L. Eoc.; N. A.	M. Eoc.; Eu.
Hyaenodontinae	M. Eoc.; Eu.	U. Eoc.; N. A., As.
Pterodon	U. Eoc.; N. A., Eu., As.	
Hyaenodon	U. Eoc.; N. A., Eu.	L. Olig.; As.
Limnocyoninae	L. Eoc.; N. A.	U. Eoc.; Eu.
Miacidae	M. Paleoc.; N. A.	U. Eoc.; Eu., As.
Viverravinae	M. Paleoc.; N. A.	U. Eoc.; Eu. L. Olig.; ?As.
Viverravus	L. Eoc.; N. A.	U. Eoc.; Eu. L. Olig.; ?As.
Miacinae	L. Eoc.; N. A.	U. Eoc.; Eu., As.
Miacis	L. Eoc.; N. A.	U. Eoc.; Eu., As.
Canidae	U. Eoc.; N. A., Eu.	L. Olig.; As.
Caninae	U. Eoc.; N. A., Eu.	U. Plioc.; As.
Canis	U. Plioc.; N. A., As.	Pleist.; Eu.
Vulpes	Pleist.; N. A., Eu., As.	
Alopex	R.; Arctic	
Simocyoninae	M. Olig.; N. A.	U. Olig.; Eu. Pleist.; As.
Amphicynodontinae	U. Eoc.; Eu.	L. Olig.; As., N. A.
Pachycynodon	Olig.; As., Eu.	L. Mioc.; N. A.
Hemicyon	?M. Mioc.; Eu.	U. Mioc.; N. A., As.
Amphicyoninae	U. Eoc.; Eu.	L. Mioc.; N. A. U. Mioc.; As.
Amphicyon	U. Olig. Eu.	M. Mioc.; N. A. U. Mioc.; As.
Borophaginae	L. Mioc.; N. A.	U. Mioc.; As.
Ursidae	M. Mioc.; Eu.	L. Plioc.; N. A. M. Plioc.; As.
Agriotherium	M. Plioc.; N. A., Eu.	M. Plioc.; As.
Indarctos	M. Plioc.; N. A., Eu., As.	
Ursus	L. Plioc.; Eu., As.	Pleist.; N. A.
Thalarctus	R., Arctic	
Procyonidae	L. Olig.; N. A., Eu.	
Plesictis	L. Olig.; N. A., Eu.	
Mustelidae	L. Olig.; N. A., Eu., As.	
Mustelinae	L. Olig.; N. A., Eu., As.	
Palaeogale	L. Olig.; N. A., Eu., As.	
Plesiogale	L. or M. Plioc.; As.	M. Plioc.; N. A.
Mustela	?U. Mioc.; N. A., Eu.	?L. Plioc.; As.
Martes	?U. Mioc., L. Plioc.; As., Eu.	U. Plioc.; N. A.
Gulo	Pleist.; N. A., Eu., As.	
Melinae	M. Mioc.; Eu.	L. Plioc.; As. M. Plioc.; N. A.
Mephitinae	U. Mioc.; Eu.	L. Plioc.; As. M. Plioc.; N. A.
Lutrinae	U. Olig.; Eu.	M. Mioc.; N. A. L. Plioc.; As.
Lutra	L. Plioc.; Eu., As.	U. Plioc.; N. A.
Felidae	?U. Eoc., L. Olig.; N. A., Eu.	L. Plioc.; As.
Nimravinae	?U. Eoc., L. Olig.; Eu.	L. Olig.; N. A. L. Plioc.; As.
Pseudaelurus	L. Mioc.; Eu.	U. Mioc.; N. A.
Felinae	L. Plioc.; Eu., As.	U. Plioc., Pleist.; N. A.
Felis	L. Plioc.; Eu.	?Plioc., Pleist.; N. A. U. Plioc.; As.
Panthera	L. Plioc.; Eu., As.	U. Plioc.; N. A.
Machairodontinae	?U. Eoc., L. Olig.; N. A.	L. Olig.; Eu. L. Plioc.; As.
Eusmilus	L. Olig.; Eu.	M. Olig.; N. A.
Machairodus	U. Mioc.; Eu.	L. Plioc.; As. M. Plioc.; N. A.

TABLE 1—*Continued*

	Earliest known occurrence	Earliest known occurrence elsewhere in Eurasia or North America
Hyaenidae	L. Plioc.; Eu., As.	U. Plioc.; N. A.
Phenacodontidae	L. Paleoc.; N. A.	L. Eoc.; Eu.
Phenacodus	U. Paleoc.; N. A.	L. Eoc.; Eu.
Meniscotheriidae	U. Paleoc.; N. A., Eu.	
Arctostylopidae	U. Paleoc.; As.	L. Eoc.; N. A.
Coryphodontidae	M. Paleoc.; N. A.	L. Eoc.; Eu. U. Eoc.; As.
Coryphodon	U. Paleoc.; N. A.	L. Eoc.; Eu.
Uintatheriidae	U. Paleoc.; N. A., As.	
Gomphotheriidae	L. Olig.; Africa	L. Mioc.; Eu., As. U. Mioc.; N. A.
Gomphotheriinae	L. Olig.; Africa	L. Mioc.; Eu., As. U. Mioc.; N. A.
Gomphotherium	L. Mioc.; Eu., As.	U. Mioc.; N. A.
Serridentinus	L. Mioc.; Eu., As.	U. Mioc.; N. A.
Tetralophodon	U. Mioc.; As.	L. Plioc.; N. A., Eu.
Anancinae	L. Plioc.; Eu.	U. Plioc.; N. A., As.
Rhynchotheriinae	L. Mioc.; Africa	U. Mioc.; N. A. M. Plioc.; As.
Rhynchotherium	L. Mioc.; Africa	U. Mioc.; N. A. M. Plioc.; As.
Platybelodontinae	U. Mioc.; As.	L. Plioc.; N. A.
Platybelodon	U. Mioc.; As.	L. Plioc.; N. A.
Mammutidae	L. Mioc.; Eu.	M. Mioc.; N. A. L. Plioc.; As.
Mammut	L. Mioc.; As.	M. Mioc.; N. A. L. Plioc.; As.
Elephantidae	U. Mioc.; As.	M. Plioc.; Eu. Pleist.; N. A.
Elephantinae	Pleist.; As., Eu., N. A.	
Mammuthus	Pleist.; As., Eu., N. A.	
Equidae	L. Eoc.; N. A., Eu.	Mioc.; As.
Hyracotheriinae	L. Eoc.; N. A., Eu.	
Hyracotherium	L. Eoc.; N. A., Eu.	
Anchitheriinae	L. Olig.; N. A.	M. Mioc.; Eu., As.
Anchitherium	L. Mioc.; N. A.	M. Mioc.; Eu., As.
Hypohippus	L. Mioc.; N. A.	U. Mioc.; As.
Equinae	L. Mioc.; N. A.	L. Plioc.; Eu., As.
Hipparion	L. Plioc.; N. A., Eu., As.	
Equus	U. Plioc.; N. A., Eu., As.	
Brontotheriidae	L. Eoc.; N. A.	U. Eoc.; Eu., As.
Telmatheriinae	M. Eoc.; N. A.	U. Eoc.; As.
Metatelmatherium	U. Eoc.; N. A., As.	
Brontopinae	M. Eoc.; N. A.	U. Eoc.; Eu., As.
Menodontinae	U. Eoc.; N. A.	L. Olig.; ?Eu.
Menodus	L. Olig.; N. A., ?Eu.	
Chalicotheriidae	U. Eoc.; N. A., As., Eu.	
Eomoropinae	U. Eoc.; N. A., As.	
Eomoropus	U. Eoc.; N. A., As.	
Chalicotheriinae	Olig.; N. A., Eu., As.	
Macrotherium	Olig.; As.	M. Mioc.; N. A. U. Mioc.; Eu.
Isectolophidae	L. Eoc.; N. A.	U. Eoc.; As.
Helaletidae	L. Eoc.; N. A.	U. Eoc.; As.
Helaletinae	L. Eoc.; N. A.	U. Eoc.; As.
Colodontinae	M. Eoc.; N. A.	U. Eoc.; As.
Desmatotherium	M. Eoc.; N. A.	U. Eoc.; As.
Colodon	L. Olig.; N. A., As.	

TABLE 1—*Concluded*

	Earliest known occurrence	Earliest known occurrence elsewhere in Eurasia or North America
Tapiridae	L. Olig.; Eu.	M. Olig.; N. A. Mioc.; As.
Protapirus	L. Olig.; Eu.	M. Olig.; N. A.
Tapirus	?U. Mioc.; L. Plioc.; Eu.	L. Plioc.; As. M. Plioc.; N. A.
Hyrachyidae	L. Eoc.; N. A.	Eoc.; ?As.
Hyrachyus	L. Eoc.; N. A.	Eoc.; ?As.
Hyracodontidae	M. Eoc.; N. A.	M. Eoc.; ?As.
Amynodontidae	U. Eoc.; N. A., As.	M. Olig.; Eu.
Amynodon	U. Eoc.; N. A., As.	
Metamynodon	L. Olig.; N. A., As.	
Rhinocerotidae	M. Eoc.; Eu.	U. Eoc.; N. A., As.
Caenopinae	M. Eoc.; Eu.	U. Eoc.; N. A., L. Mioc.; As.
Teleoceratinae	U. Olig.; Eu.	U. Mioc.; N. A.
Dichobunidae	L. Eoc.; N. A., Eu.	
Dichobuninae	L. Eoc.; N. A., Eu.	
Choeropotamidae	L. Eoc.; N. A.	M. Eoc.; As. U. Eoc.; Eu.
Entelodontidae	U. Eoc.; N. A.	?U. Eoc., L. Olig.; As. L. Olig.; Eu.
Entelodon	L. Olig.; Eu., ?N. A.	
Tayassuidae	L. Olig.; N. A., Eu.	L. Plioc.; As.
Anthracotheriidae	M. Eoc.; Eu.	U. Eoc.; As. L. Olig.; N. A.
Bothriodon	L. Olig.; Eu., N. A.	
Camelidae	U. Eoc.; N. A.	Pleist.; As., Eu.
Camelinae	U. Olig.; N. A.	Pleist.; As., Eu.
Hypertragulidae	U. Eoc.; N. A., As.	
Cervidae	L. Olig.; As.	U. Olig.; Eu. L. Mioc.; N. A.
Palaeomerycinae	L. Olig.; As.	U. Olig.; Eu. L. Mioc.; N. A.
Cervinae	L. Plioc.; Eu., As.	?U. Plioc., Pleist.; N. A.
Cervus	M. Plioc.; As.	U. Plioc.; Eu. Pleist.; N. A.
Odocoileinae	L. Plioc.; Eu., As.	Pleist.; N. A.
Alce	Pleist.; N. A., Eu., As.	
Rangifer	Pleist.; N. A., Eu., As.	
Bovidae	L. Mioc.; Eu.	L. Plioc.; As. Pleist.; N. A.
Bovinae	L. Mioc.; Eu.	L. Plioc.; As. Pleist.; N. A.
Bos	Pleist.; Eu., As., N. A. (Alaska only).	
Bison	U. Plioc.; As.	Pleist.; N. A., Eu.
Ovis	U. Plioc.; As.	Pleist.; N. A.

relations and placing of epoch and subepoch boundaries are perforce somewhat arbitrary and personal. The system followed as nearly as possible throughout this paper is shown in Table 2.

TIMES OF MIGRATION

The occurrence of the same group of mammals on the two different land masses is taken as prima-facie evidence that migration has occurred.[4] The latest possible date

[4] It is a conceivable alternative that some taxonomic groups are morphological but not phylogenetic and that they arose independently on the two continents. This has been claimed for many groups, but, if true at all, it must (in my opinion) be highly exceptional and can be ignored in an over-all view.

TABLE 2.—*Approximate correlation used in preparing this paper*

E, early; M, middle; L, late.

Epoch		North America (Stages)	Europe (Stages)		Central or East Asia (Representative local faunas)	South Asia (Formations)
Pliocene	L	Blancan	Villafranchian		Nihowan	Pinjor
			Astian			
	M	Hemphillian	Plaisancian		Ertemte	Tatrot
						Dhok Pathan
	E	Clarendonian	Pontian		Paote	Nagri
						Chinji
Miocene	L	Barstovian	Sarmatian		Tung Gur	Kamlial
	M	Hemingfordian	Vindobonian	Tortonian	?	?
				Helvetian		
			Burdigalian			
	E	Arikareean	Aquitanian		Loh	
Oligocene	L	Whitneyan	Chattian		Hsanda Gol	
	M	Orellan	Rupelian		Houldjin	
	E	Chadronian	Sannoisian		Ardyn Obo	
Eocene	L	Duchesnean	Ludian		Shara Murun	Pondaung
		Uintan	Bartonian		Irdin Manha	?
	M	Bridgerian	Lutetian		?	
	E	Wasatchian	Cuisian			
			Sparnacian			
Late Paleocene		Clarkforkian	Thanetian		Gashato	
		Tiffanian				

for the migration of any particular group is the later of the two dates of first known occurrence on the two land masses. How much earlier than this the migration actually occurred does not automatically appear from the observational data. It can hardly be supposed that the first *known* occurrence is always at or near the time of the

first real occurrence. On the other hand, in the better-known and more intensively collected groups, especially the carnivores and ungulates (in the broadest sense), or Ferungulata of my classification, first records probably tend to be fairly near the true date of migration. It is also likely that first records of common genera are on an

TABLE 3.—*Tabulation of the later of two dates of first occurrence, either in North America or in Eurasia, of groups of land mammals known from both regions*

Date	Genera	Families	Independent items, among families, subfamilies, and genera					
			Insectivores, lagomorphs, rodents	Total nonferungulates	Carnivores	Perissodactyls and artiodactyls	Total ferungulates	Total land mammals
Recent	5	0	3	3	2	0	2	5
Pleistocene	22	4	10	11	4	7	12	23
Pliocene:								
Late	9	1	5	5	6	1	8	13
Middle	6	2	3	3	6	1	7	10
Early	5	1	3	3	0	1	3	6
Miocene:								
Late	8	2	6	6	4	2	9	15
Middle	5	1	2	2	2	2	5	7
Early	1	1	1	1	2	1	3	4
Oligocene:								
Late	2	2	4	4	1	0	1	5
Middle	4	1	2	2	1	1	2	4
Early	9	7	3	3	6	7	13	16
Eocene:								
Late	11	12	2	3	9	10	19	22
Middle	1	2	0	0	1	2	3	3
Early	10	15	3	8	4	3	10	18
Late Paleocene	4	7	1	4	3	0	5	9

average somewhat nearer the migration date than are first records of more inclusive taxonomic groups.

Table 3 lists pertinent data in two ways, by totals for genera and families separately, and by independent items of evidence within selected categories of classification. By "independent items" is meant records of family, subfamily, or generic common occurrence (as in Table 1) providing evidence of a separate migration. Thus if the record of common occurrence is for one genus belonging to a given subfamily and family, all appearing at the same time and on the basis of that genus, this record, although involving three taxonomic groups, is only one item of evidence. If, however, a family (but not an included genus) first becomes common to the two continents, and an included genus later becomes common to them, these are two items of evidence. In Eurasia no Tertiary mammals have been found before the late Paleocene, and even the late Paleocene faunas are very poorly known. These are tabulated, but should not be taken too seriously. Certain of the data of the table are given in graphic form in Figure 1.

Tabulation by genera follows very nearly the same pattern as the "independent-

item" tabulations for ferungulates and for all land mammals. The carnivore pattern differs in the absence of a Pleistocene peak. For perissodactyls and artiodactyls, the pattern differs more markedly, especially in showing relatively little evidence of migration in the early Eocene, late Miocene, and late Pliocene. These discrepancies

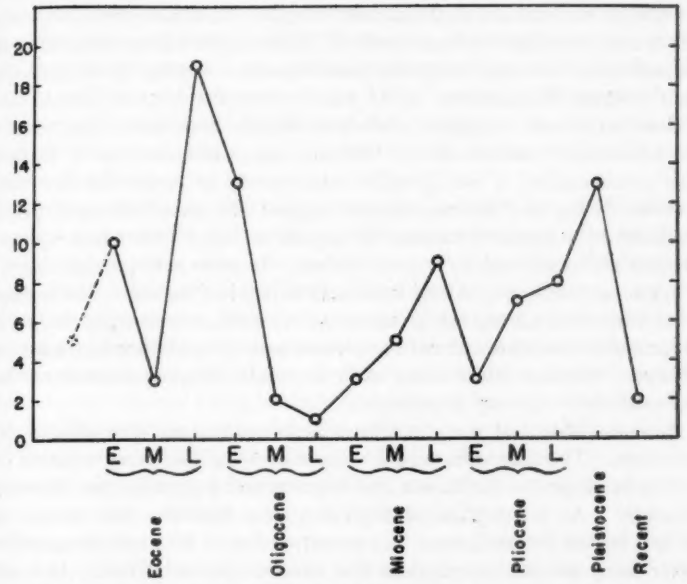


FIGURE 1.—*Items of evidence of migration of land mammals between Eurasia and North America, ferungulates only*

Data from Table 3.

seem to be significant, but they argue not against the existence of a migration route at those times but in favor of taxonomic selectivity in those migrations, a point to be mentioned again later. The data for insectivores, lagomorphs, and rodents or, collectively, the microfauna show something of the same pattern but less clearly and in somewhat random fashion. In fact, the paleontological sampling of the microfauna is very much less complete than for the larger ferungulates, and the random influence of inadequate sampling would be expected.

These data indicate that there were particularly strong interchanges of mammalian faunas between Eurasia and North America around the beginning of or during the early Eocene, late Eocene, early Oligocene, late Miocene, middle to late Pliocene, and Pleistocene. There is some evidence of migration at all times, but this evidence does not, in some cases, warrant the conclusion that any appreciable interchange was really occurring. After a time of intensive intermigration, it is improbable that all the groups involved will be picked up immediately in the record. The occurence of a few first records after such an episode therefore has relatively little value as evidence

that the interchange was actively continuing. This consideration applies especially to the middle Eocene, middle and late Oligocene, Recent, and, with less force, to the early Pliocene.[5]

Interpretation of the apparent low point of migration in the early Pliocene is somewhat dubious. An earlier draft tabulation showed a moderate high in the early Pliocene and an extreme low in the middle Pliocene. It was evident, however, that this low, at least, was likely to be an artifact. Some authors do not separate a middle Pliocene subepoch, but only early and late Pliocene. Among all students there is particularly strong disagreement as to exactly how the Pliocene should be subdivided and correlated. Compiled data here involve even more than usual of inaccuracy and lack of common focus. With the help, particularly, of P. O. McGrew (personal comunication) it was possible subsequently to revise the first draft by more precise dating of Pliocene migrants against the scale here used (Table 2). This eradicated the apparent extreme low in the middle Pliocene but replaced the moderate early Pliocene high by a moderate low. In other words, the dating of some known migration was simply shifted from early to middle Pliocene. The fact appears to be that there was, among the groups now on record, a temporary decline in migration (probably moderate and not complete or strong) some time in the first half of the Pliocene. Whether this is called early or middle Pliocene depends on the correlations used and is not very important.

The data available and the conclusions here reached are incapable of delicate discrimination. The time units used average over 4½ million years in length (with a tendency to be longer for the Eocene and Miocene and shorter for the Oligocene and post-Miocene). An interruption of migration for a time less than several million years might not be detected, even in a tentative way. It is entirely possible that there were many shorter interruptions that cannot now be inferred. It is unlikely that any important intermigration is missed altogether, but it is entirely possible that some of them are misplaced and even more likely that separate migrations, at intervals up to 2 or 3 million years, have been combined into one. Greater refinement in these respects would require quite exact intercontinental correlations of the mammal-bearing strata. At present these correlations are rather dubious even on the broader time scale here used, and this inevitably involves a general blurring of the whole picture, which cannot be sharply focused on closely synchronous events on the two land masses involved.

In several cases, major climaxes of Tertiary migration involve the end of one epoch and beginning of the next, especially in the late Eocene and early Oligocene and in the late Pliocene and early Pleistocene. There is some reason to think that the same would be found true of the first climax (early Eocene) if we knew more about the Paleocene and that this would involve both late Paleocene and early Eocene. The climax that here appears as late Miocene also seems to be dual (or multiple), and by a slight shifting of the boundary, in accordance with some views on correlation, it would involve both late Miocene and early Pliocene. Only for the late Oligocene and

[5] Whether such times represent a gradual decrease as faunal equilibrium is attained or whether they represent a definite stoppage because of the breaking down of a migration route will be discussed later. It may, however, be noted here that faunal interchange, faunal resemblance, and availability of migration routes, although obviously interrelated, are three separate problems. It does not automatically follow that a land bridge rose and fell in synchrony with increases and decreases of migration or of faunal resemblance.

early Miocene, both times of low intermigration, is there no evidence of a tendency for increased migration around and on both sides of an epoch boundary. A first hypothesis for the apparent duality (or multiplicity) of each climax would be that this is caused by the lack of focus previously mentioned and that migrations really approximately synchronous have been distributed around the epoch boundaries by inexact correlation. This is probably in part correct, for instance as regards the late Pliocene-Pleistocene migrations. Most of the first occurrences entered as late Pliocene are in strata of questionable age often referred to the Pleistocene, and some occurrences really contemporaneous are probably entered as Pleistocene. Even in this case, however, there is other, fairly conclusive evidence that there were at least two waves or climaxes of interchange, one near the Plio-Pleistocene boundary and one later in the Pleistocene.

The stated hypothesis also fails fully to explain the other cases under consideration. Although here, too, dubious correlation doubtless plays a part, the evidence from single areas suggests that successive migrations and not merely a blurred or long-continued single migration are involved. Thus whether the American Duchesnean is or is not contemporaneous with the European Ludian, and whether either or both are or are not considered as late Eocene in age, there were almost surely at least two distinct waves of intermigration around this epoch boundary. In North America, evidence for one is mainly found in the Uintan and for the other mainly in the Chadronian, with the intermediate Duchesnean, with its inadequately known fauna, intermediate or anomalous. It is most improbable that the apparent general tendency for major intermigrations to be dual (or possibly multiple) is an artifact caused by the placing of the epoch boundaries or by faults in correlation.

It is, of course, uncertain that there were only two main migrational phases on each of these occasions. There may well have been multiple waves that have been oversimplified into two by the factors making for inexactness in these deductions. Nor is it clear why there were two or more migrations instead of one. Perhaps the most obvious hypothesis would be an interruption of the migration route, with renewed migration when it was reconstituted. This is a possibility, but there is, insofar as I know, no good evidence for it except the probable double or multiple nature of the migration, and the hypothesis, in itself, is probably inadequate to account for that phenomenon. The earlier migratory phase was in each case strong enough to have established an approximate equilibrium between the continents. The interruption, if it occurred, apparently was not long enough for the establishment of any striking disequilibrium. Reconstitution of the migration route would not, it would then seem, be a sufficient stimulus, by itself, for another major intermigration.

Advanced with strong reservations as to completeness and adequacy of evidence, the following are, then, tentative general conclusions as to successive migrations in the Tertiary.

Paleocene:	Early:	Unknown
	Middle:	
	Late:	Possibly strong intermigration, but evidence very inadequate.
Eocene:	Early:	Strong intermigration, distinct from Paleocene intermigration.
	Middle:	Little or no intermigration.
	Late:	Strong intermigration.

Oligocene:	Early:	Strong intermigration, separate, at least in part, from the late Eocene migration.
	Middle:	Little or no intermigration.
	Late:	Little or no intermigration.
Miocene:	Early:	Slight intermigration.
	Middle:	Some, not strong but probably increased, intermigration.
	Late:	Strong intermigration, probably with two (or more) phases of which the later somewhat overlapped the nominal Pliocene boundary.
Pliocene:	Early:	Probably decreased intermigration following the Mio-Pliocene climax phase.
	Middle:	Renewed increase in intermigration, not reaching its climax in this subepoch.
	Late:	Continued increase in intermigration, probably reaching a climax phase near end.
Pleistocene:		Strong intermigration at the Plio-Pleistocene transition and another mid-Pleistocene surge waning toward the end of the epoch.
Recent:		Little or no intermigration, except casually and locally.

DIRECTIONS OF MIGRATIONS

The problem of direction of migration would seem to be relatively simple. It might be supposed that a given group or its ancestors would appear earlier on one land mass than on another, and that the direction of migration would then be obvious. As a matter of fact, there are relatively few groups for which the direction of migration can be given with any strong assurance. This is in most cases one of the greatest uncertainties regarding the geographical history of Holarctic mammals.

There are many groups that are known first from North America, but at a time unrepresented by known or well-known Eurasian faunas, and that do turn up in Eurasia among the earliest subsequent faunas adequately known there. Certainly it should not be assumed on this evidence that migration was from the New World to the Old. Among these groups are particularly those that appear in the Cretaceous and Paleocene in North America and in the late Paleocene or early Eocene in Eurasia—about 15 families and a few genera. It has been argued that the sudden appearance of the varied early Paleocene fauna in North America indicates immigration and that such a mass movement must have come from Eurasia. If so, the migration was in the opposite direction to that indicated by the (wholly unreliable) evidence of place of first known appearance. This is not, however, the only possible explanation as to the origin of this fauna, and the hypothesis is without objective evidence. In a record even remotely factual, direction of migration in all these cases must now be recorded as unknown.

An even larger number of groups appear simultaneously, or as nearly so as accidents of collecting and uncertainties of correlation permit, in both Eurasia and North America and have no known ancestors in either region. Here, again, the evidence really does not warrant hazarding a guess as to the direction in which they migrated. It used to be argued that such simultaneity of appearance in North America and Europe indicated dispersal from an area midway between the two, *i.e.*, from Asia. The numerous faunas now known from Asia, however, have failed to support this inference. They do not necessarily definitively disprove it, but the absence of any real corroboration makes the hypothesis shaky and emphasizes that the direction of

migration for these groups is so completely unknown that the hypothesis has no working value at present. Outstanding among the groups in this category are those that appear at the beginning of the Eocene in the two hemispheres, but there are also later examples.

In other instances, groups appear at about the same time on the two continents but have either a known ancestry or a variety of earlier relatives on one and not on the other. This is usually true of groups that are really well known by now, such as the horses. In such cases the evidence strongly suggests the direction of migration. I believe, indeed, that such evidence is more reliable than any evidence involving only earlier appearance in one area than in another.

The frequency with which groups do appear simultaneously in both regions, insofar as can be judged by our admittedly still very approximate correlations, amounts to a rule, in spite of various exceptions. This suggests that migration is usually rapid, geologically speaking, or without perceptible lag unless a barrier exists. Conversely, the failure of a group to appear immediately on a second continent when it appears on one is not likely to be because of a measurable homotaxial retardation in spread but is, as initial hypotheses, best ascribed either to lack of discovery or to the presence of a barrier. This barrier may be the absence of a land route or may be physiographic, ecological, etc. The point is discussed elsewhere, but it may be noted here that between North America and Eurasia long-continued failure to migrate is probably not to be ascribed either to slow rates of migration or to absence of a land route and implies an ecological (biotic, climatic, etc.) barrier for that particular group.

The following summarizes the evidence on direction of migration for (and within) each family common to North America and Eurasia:

Ptilodontidae: No good evidence.

Didelphidae: Some suggestion that migration was from North America to Eurasia, but the Eurasian Cretaceous mammals are too poorly known for this to have any real force. The evidence that the genus *Peratherium* migrated in this direction is somewhat better than for the family as whole, but still inadequate.

Leptictidae: No good evidence.

Erinaceidae: Very dubious. The family is known earlier in North America than in Eurasia but has no known ancestry in either region, and the animals are small and are rare at most horizons. The Erinaceinae seem to have migrated from Eurasia to North America, but the phylogeny of the whole family is still obscure.

Nyctitheriidae: No good evidence.

Soricidae: Perhaps migrated from Eurasia to North America. The Soricinae and *Sorex* are known earlier in Eurasia, and the Crocidurinae at nearly the same time in both. Again, these are small and usually rare animals, and the record is deficient.

Talpidae: The known Talpinae are older in Europe, where the whole family may have originated, but the Scalopinae seem to be of North American origin and to be late migrants to Asia.

Pantolestidae: No good evidence.

Plesiadapidae: No good evidence.

Adapidae: No good evidence.

Anaptomorphidae: No good evidence.

Apatemyidae: No good evidence.

Tillotheriidae: No good evidence.

Ochotonidae: Crucial evidence is lacking, but what is known hints that migration of the family and of *Desmatolagus* and *Ochotona* was from Eurasia to North America.

Leporidae: Old World origin is hinted, but the evidence is very incomplete. On the other hand, there was considerable deployment in North America, and some lines, such as *Hypolagus*, seem to have migrated from there to Eurasia. Leporinae and *Lepus* perhaps migrated in the opposite direction. There was probably a complex interchange that is poorly understood as yet.

Ischyromyidae: No good evidence as to the group as a whole or its earlier members. The major radiation seems, however, to have been North American, and there is some inconclusive likelihood that the Sciuravinae and *Prosciurus* (or a close relative) and the Cylindrodontinae and *Ardynomys* migrated from North America to Asia.

Aplodontidae: Ultimate origin unknown, but migration of known forms was almost certainly from North America to Asia.

Eomyidae: Appear about simultaneously in Europe and North America. Perhaps of Eurasian origin.

Sciuridae: The history of the family was evidently very complex and is insufficiently known. Direction of migration of groups common to North America and Eurasia is hardly hinted by the data now in hand, although it is possible that the ground squirrels evolved mainly in and radiated from North America.

Castoridae: The family has a long, continuous history in North America, and migration may have been from there to Eurasia. This could also be true of the various common genera and is very probably true of *Dipoides*. More evidence will be adduced by studies now in progress (Stout, unpublished).

Cricetidae: The family and all the common genera appear at so nearly the same times in Eurasia and North America that the apparent differences in each case may be accidents of preservation and collecting. It is, however, possible that the Cricetinae migrated from Eurasia to North America and the later Microtinae in the opposite direction. Common genera are mostly boreal and of unknown more exact origin.

Zapodidae: Older and more varied in Eurasia, as far as known, and probably arose there. The Zapodinae and *Zapus*, however, may represent a North American branch with reverse migration to Asia.

Arctocyonidae: No good evidence.

Mesonychidae: No good evidence.

Oxyaenidae: No good evidence.

Hyaenodontidae: The family, *Sinopa*, and the Limnocyoninae are known earlier in North America, but the evidence that they migrated thence to Eurasia is of little or no value. The Hyaenodontinae and *Hyaenodon* may have migrated in the opposite direction, but this, too, is uncertain.

Miacidae: On the face of the evidence, it would appear that the family and all lesser common groups migrated from North America to Eurasia. There is, however, an anomaly here. The Viverridae seem to be derived from the Miacidae but appear as early as the latter in Europe and are wholly unknown in North America. This suggests an older, unknown Eurasian group of miacids.

Canidae: The family and most of the included common groups appear almost simultaneously in the New and Old World. There was probably rather complex intermigration, but the direction in any given case is extremely dubious. The Amphicynodontinae, *Pachycynodon*, *Hemicyon*, and *Amphicyon* seem to be from Eurasia, and the Borophaginae from North America, but these directions of migration are also dubious.

Ursidae: The oldest reasonably definite ursids are Eurasian, and the evidence is good that deployment, including that of the common genera, was from there to North America.

Procyonidae: It has been generally supposed that this family was of New World origin and mainly, if not wholly, confined to this hemisphere. It has, however, recently been found that some of the members of the earliest canid-mustelid complex had distinctly procyonid characters, if not themselves definite procyonids, both in Europe and in North America (Hough, personal communication). This leaves the direction of their basic migration uncertain. The Ailurinae probably arose in Eurasia from this ancient stock and do not represent a separate, later migration.

Mustelidae: Appearance of the Mustelidae, Mustelinae, and all the musteline genera common to North America and Eurasia is essentially simultaneous on the two land masses. Melinae, Mephitinae, and Lutrinae are considerably older in Eurasia, insofar as known. It is possible, but very un-

certain, that most of the migration was from the Old World to the New. (If this is correct, if might suggest a similar history for the earliest procyonids, *see above*.)

Felidae: It is sometimes assumed that the family and most if not all of the included common subfamilies and genera migrated from the Old World to the New, and this is consistent with the evidence, but the evidence is highly incomplete as regards direction of migration.

Hyaenidae: New World occurrence is reported by Stirton and Christian (1940). If one accepts the record as correct, on this authority, it clearly involves migration from Eurasia to North America.

Phenacodontidae: No good evidence.

Meniscotheriidae: No good evidence.

Arctostylopidae: No good evidence. Late Paleocene occurrence in Asia and early Eocene occurrence in North America of this group, allied to the more primitive notoungulates, was hailed as indicating the migration of this order from Asia to South America through North America. The case is, however, by no means so simple. Both more primitive and more advanced notoungulates were present in South America by about the late Paleocene, and the Asiatic forms could even represent waifs reaching there from North America.

Coryphodontidae: No good evidence.

Uintatheriidae: No good evidence.

Gomphotheriidae: It is reasonably well established that not only this family, the four included common subfamilies, and the five included common genera, but also all the other proboscideans, down to genera, at least, common to the two regions migrated from the Old World to the New.

Mammutidae: Migration from the Old World to the New is very probable, as for the Gomphotheriidae.

Elephantidae: Migration from Asia to North America is well established, as for the preceding proboscideans.

Equidae: There is no good evidence as to the place of origin of the family as a whole or of its earliest representatives, the Hyracotheriinae or *Hyracotherium*. After this first appearance, however, the main line of equid evolution was in North America, and most, perhaps all, migration was away from that continent. The Anchitheriinae, *Anchitherium*, *Hypohippus*, Equinae, and *Hipparion* (or its immediate ancestor) almost certainly migrated from North America to Eurasia. This has usually been considered true of *Equus* also, but now McGrew (1944) claims that although *Equus* (*Hippotigris*) had this history, *Equus* (*Equus*) reached North America by return migration from Asia—an example of the fact that even the apparently best-founded conclusions in this field may still be disputable.

Brontotheriidae: Origin of the family unknown. The data are insufficient but hint that most of the subsequent migration was from North America to Eurasia.

Chalicotheriidae: Origin unknown, and after the first migration the family may have developed independently in the two regions, but it may be a little more likely that *Macrotherium* and the ancestry of *Moropus* were migrants from Asia to North America.

Isectolophidae: The record suggests migration from North America to Asia, but family origin is unknown, and the evidence is wholly inadequate.

Helaletidae: Remarks on the Isectolophidae apply equally to this family.

Tapiridae: The North American series may be more direct and central, but the scanty evidence seems inadequate to indicate the direction of migration.

Hyrachyidae: Occurrence outside North America is rather dubious, and if such occurrence is correct the direction of migration is not known.

Hyracodontidae: Same remarks as for Hyrachyidae.

Amynodontidae: Studies now in hand (H. E. Wood, personal communication) reveal no good evidence for migration from Eurasia to North America and suggest that the group evolved in North America and was immigrant in Eurasia.

Rhinocerotidae: There is no good evidence for the family as a whole or the Caenopinae, but the Teleoceratinae probably migrated from Eurasia to North America.

Dichobunidae: No good evidence.

Choeropotamidae: Somewhat earlier in North America, but evidence very inconclusive.

Entelodontidae: Essentially simultaneous in the two regions, and no impressive evidence on direction of migration.

Tayassuidae: It is generally assumed that this group arose in North America and occurs in Eurasia only as an immigrant, if at all. Yet there is a probable tayassuid as early in Europe as in North America and, if, as is probable, there was a common ancestry with the Suidae, the ancestry of the earliest New World forms probably migrated from Eurasia.

Anthracotheriidae: Apparently an Old World group one line of which migrated to North America.

Camelidae: The origin of the family is unknown, but the later Eurasian camels clearly represent migration from North America.

Hypertragulidae: No good evidence.

Cervidae: Apparently a basically Old World group with common occurrences between the two representing in each case a migration to the New World. Early migrants underwent marked differentiation in America, but apparently without reverse migration back to Asia.

Bovidae: Quite surely an Old World group, each New World line or genus representing migration from Asia to North America.

TAXONOMY OF MIGRANTS AND NONMIGRANTS

GENERAL CONSIDERATIONS

The following lists provide a running summary of the important elements in the Eurasian and North American land mammalian faunas in the successive subepochs since the Paleocene. Migrant groups are listed in more detail and are entered in the earliest subepoch of known common occurrence. As emphasized above, the real date of migration may have been earlier in many cases, especially those of the smaller and rarer animals. Orders are entered in each case, but entry as a migrant of a family, subfamily, or genus indicates that this is the first migration in which that particular unit is known to have participated. For instance, "Equidae" appears as a migrant family only in the early Eocene, but some subfamilies and genera of Equidae are entered later, when they migrated.

The nonmigrants are given in less detail but sufficient to show the general characters of the parts of the faunas distinctive of each continental mass at given times. The negative fact, that a group did not migrate, is not open to positive proof, and later discovery will doubtless show that some groups listed as nonmigrant did, in fact, migrate at the stated time. It is, however, rather unlikely that this is true of many of the groups listed.

Direction of migration is also stated, when it is possible to hazard a guess as to this. As previously emphasized, the direction is seldom definitely known, and attention is called to the fact that these are listed only as *perhaps* the directions of migration. Some idea of the degree of certainty (or uncertainty) in given cases can be gathered from the preceding section of this paper.

EARLY EOCENE

Important migrants (direction of migration is not known in any case)

Insectivora: Pantolestidae, *Palaeosinopa*
Primates: Adapidae; Apatemyidae; Anaptomorphidae
Tillodontia: Tillotheriidae, *Esthonyx*
Taeniodonta: Stylinodontidae, *Ectoganus*

Rodentia: Ischyromyidae, Paramyinae
Carnivora: *Pachyaena*; Oxyaenidae, *Palaeonictis*; Hyaenodontidae (Arctocyonidae and Mesonychidae had already migrated in the Paleocene)
Condylarthra: Phenacodontidae, *Phenacodus*
Pantodonta: Coryphodontidae, *Coryphodon*
Perissodactyla: Equidae, *Hyracotherium*
Artiodactyla: Dichobunidae

Important nonmigrants

In Eurasia:
Perissadactyla: Palaeotheriidae, Lophiodontidae
In North America:[6]
Palaeanodonta
Carnivora: Oxyaeninae, Miacidae
Condylarthra: Hyopsodontinae
Perissodactyla: Brontotheriidae, Isectolophidae, Helaletidae
Artiodactyla: Choeropotamidae

The early Eocene migrants were very numerous and constituted, in themselves, a complete and balanced fauna. This interchange is unlike any later one in that it seems to include the major part of the faunas of the two areas. Indeed the impression is that Eurasia and North America were zoogeographically essentially a single region at this time. The probable or possible nonmigrants include rather rare groups of peculiar ecological type (palaeanodonts) or groups ecologically similar to but on the whole more specialized than those that did migrate at this time (ungulates). Of these, most either became extinct early in the Tertiary (palaeotheres and lophiodonts) or did migrate sooner or later.

MIDDLE EOCENE

Apparent migrants (direction of migration unknown)

Carnivora: *Sinopa*
Perissodactyla: Hyracodontidae
Artiodactyla: Choeropotamidae

Important nonmigrants

In Eurasia:
Primates: Plesiadapidae*
Perissodactyla: Palaeotheriidae; Lophiodontidae; Rhinocerotidae
Artiodactyla: Cebochoeridae; Anoplotheriidae; Anthracotheriidae; Xiphodontidae

[6] The nonmigrant status of all these groups is particularly dubious. Any or all of them may well have migrated in the early Eocene, which is quite inadequately known in Eurasia. Many of them are known to have migrated at or before later dates, or to have had close allies which did so.

* Had migrated earlier but are not known on both continents at this time and may have died out on one. The Equidae had probably become extinct in Eurasia but were, of course, reintroduced later.

In North America:
Insectivora: Leptictidae*; Pantolestidae*; Nyctitheriidae*; Mixodectidae
Tillodontia: Tillotheriidae
Taeniodonta: Stylinodontidae*
Palaeanodonta: Metacheiromyidae
Carnivora: Miacidae
Condylarthra: Hyopsodontidae
Perissodactyla: Equidae*; Brontotheriidae; Isectolophidae; Helaletidae; Hyrachyidae

In both Eurasia and North America, but apparently not migrant at this time

Primates: Adapidae; Anaptomorphidae; Apatemyidae
Rodentia: Ischyromyidae†
Carnivora: Mesonychidae†; Oxyaenidae†; Hyaenodontidae
Pantodonta: Coryphodontidae†
Dinocerata: Uintatheriidae†
Artiodactyla: Dichobunidae

It is improbable that there was any migration between Eurasia and North America in the middle Eocene. The apparent migrants are of somewhat doubtful relationships, and if the record is correct their migration may well have occurred earlier. The faunal divergence of the two areas, which had begun in the latter part of the early Eocene, continued in the middle Eocene and was not counterbalanced by intermigration. Groups still common to the two regions developed distinctive types in each. Especially noteworthy are the strikingly different sorts of perissodactyls in North America and of both perissodactyls and artiodactyls in Eurasia.

LATE EOCENE

Important migrants

Perhaps from Eurasia to North America:
Lagomorpha: Leporidae
Rodentia: Eomyidae
Carnivora: Hyaenodontinae, *Pterodon*, *Hyaenodon*; Felidae, Machairodontinae (migration very dubious here and may have been later)
Perissodactyla: Rhinocerotidae, Caenopinae
Perhaps from North America to Eurasia:
Insectivora: Erinaceidae, Echinosoricinae? (Migration at this time and direction of migration both very doubtful.)
Carnivora: Oxyaeninae; Limnocyoninae; Miacidae (indirect evidence suggests migration was earlier), *Viverravus*, *Miacis*
Perissodactyla: Brontotheriidae, Telmatheriinae, *Metatelmatherium*, Brontopinae; Isectolophidae; Helaletidae, Helaletinae, Colodontinae, *Desmatotherium*; Amynodontinae, *Amynodon*

* Had migrated earlier but are not known on both continents at this time and may have died out on one. The Equidae had probably become extinct in Eurasia but were, of course, reintroduced later.
† Known earlier and later, but not exactly at this time, in Eurasia. It is possible, or probable, that they continued to live there.

Direction of migration wholly dubious:
Carnivora: Canidae, Caninae
Perissodactyla: Chalicotheriidae, Eomoropinae, *Eomoropus*
Artiodactyla: Entelodontidae; Hypertragulidae

Important nonmigrants

In Eurasia:
Insectivora: Talpidae? (Small and rare; time of migration very uncertain.)
Rodentia: Pseudosciuridae; Theridomyidae
Carnivora: Viverridae? (late Eocene age dubious); Felidae? (May have migrated at this time), Nimravinae
Perissodactyla: Palaeotheriidae; Lophiodontidae
Artiodactyla: Cebochoeridae; Anoplotheriidae; Anthracotheriidae; Cainotheriidae; Xiphodontidae, Gelocidae
In North America:
Perissodactyla: Equidae
Artiodactyla: Agriochoeridae; Merycoidodontidae; Camelidae

The individuality of the late Eocene faunal interchange is not too clear, particularly because the distribution and facies of known Eocene faunas (especially in Asia) are not well suited to following details of history in that epoch. Some of the apparent migrants at this time may well be late discoveries of groups that had migrated earlier, and the lack of middle Eocene interchange was possibly less absolute than now appears. On the other hand, the late Eocene migrants might be considered the beginning of the more strongly characterized early Oligocene migration, although there do seem to be at least two distinct waves. The interchange is much less balanced than in the early Eocene, and, aside from a few carnivores, the last, specialized creodonts, and a very small variety of early fissipeds, it consists mainly of browsing ungulates, in most cases relatively primitive members of what were soon to become highly specialized lines. It is striking that most of the diverging perissodactyl groups differentiated during the Eocene migrated at this time but that most of the analogously differentiating artiodactyls did not. It is this failure of the characteristic artiodactyls of each continent to migrate to the other that especially stamps this interchange and that causes it to leave the two continental faunas sharply distinctive in character in spite of extensive migration of other groups. This is, however, less true if attention is concentrated on the Asiatic faunas in Eurasia; most of the nonmigrants are European rather than Asiatic. In any case, the basic divergence by evolution *in situ* in each region, so striking in the middle Eocene, continued, but some of the divergent groups began to intermigrate.

EARLY OLIGOCENE

Important migrants

Perhaps from Eurasia to North America:
Insectivora: Soricidae, Soricinae
Lagomorpha: Ochotonidae, *Desmatolagus*

Rodentia: Cricetidae, Cricetinae (migration may have been later)
Carnivora: Amphicynodontinae; Procyonidae, *Plesictis*; Mustelidae, Mustelinae, *Palaeogale*; Felidae (migration may have begun earlier), Nimravinae, Machairodontinae (perhaps earlier), *Eusmilus*
Artiodactyla: Tayassuidae; Anthracotheriidae, *Bothriodon*

Perhaps from North America to Eurasia:
Rodentia: Sciuravinae, *Prosciurus*; Cylindrodontinae, *Ardynomys*
Perissodactyla: Menodontinae, *Menodus* (identification in Eurasia uncertain); *Metamynodon*

Direction of migration wholly dubious:
Perissodactyla: Chalicotheriinae
Artiodactyla: *Entelodon* (generic identity dubious)

Important nonmigrants

In Eurasia:
Insectivora: Talpidae (time of migration very uncertain)
Primates: Anagalidae
Rodentia: Pseudosciuridae; Theridomyidae; Cricetodontini
Carnivora: Amphicyoninae; Viverridae
Perissodactyla: Palaeotheriidae
Artiodactyla: Choeropotamidae (had migrated earlier but apparently became extinct in North America without reintroduction); Cebochoeridae; Suidae; Anoplotheriidae; Cainotheriidae; Xiphodontidae; Gelocidae; Cervidae

In North America:
Insectivora: Leptictidae
Rodentia: Paramyinae (had migrated earlier, but apparently continued in North America without further migration); Ischyromyinae; Heteromyidae; Castoridae
Perissodactyla: Anchitheriinae
Artiodactyla: Agriochoeridae, Merycoidodontidae; Camelidae; Hypertragulidae (had migrated previously but apparently became extinct except in North America and did not emigrate again from there); Protoceratidae

This is one of the most distinctive and generally recognized of the faunal interchanges here under consideration, but, as the preceding data show, it apparently involved only a rather small and peculiarly assorted part of the faunas of the two continents. Its outstanding feature is the great expansion of specialized fissiped carnivores, which had perhaps differentiated in the Old World and now spread to the New in greater variety than at any other time. These were soon to replace all the more archaic types, and the general pattern of carnivore distribution was established, as regards its broadest outlines, at this time. The failure of the viverrids to migrate is striking. Among the ungulates, the sharp distinction in artiodactyls of the two continents continues and increases. The native groups show still greater expansion on each continent, and only a few rather unimportant forms migrate. Perissodactyl migration was also unspectacular at this time and was almost confined to further interchange within a few groups (chalicotheres, titanotheres, and rhinoceroses) that had already been involved in intercontinental migration.

MIDDLE AND LATE OLIGOCENE

Apparent migrants (of record; early Oligocene migration is more probable in each case but is not yet established by fossils; directions dubious)

Insectivora: Talpidae
Rodentia: Sciuravinae, *Prosciurus*; Castoridae; Cricetidae, Cricetinae, *Eumys*
Carnivora: Simocyoninae

Important nonmigrants

In Eurasia:
Insectivora: Dimylidae
Lagomorpha: Ochotonidae
Rodentia: Pseudosciuridae; Theridomyidae; Rhizomyidae
Perissodactyla: Brontotheriidae (now extinct in North America); Chalicotheriidae (known earlier and later in North America, but perhaps absent at this time)
Artiodactyla: Dichobunidae; Choeropotamidae; Suidae; Cainotheriidae; Cervidae

In North America:
Insectivora: Leptictidae
Rodentia: Geomyidae; Heteromyidae
Perissodactyla: Equidae (extinct in Europe and not reintroduced until Miocene); Helaletidae; Hyracodontidae
Artiodactyla: Entelodontidae; Tayassuidae (earlier and later in Eurasia, perhaps present there at this time); Agriochoeridae; Merycoidodontidae; Camelidae; Hypertragulidae

Present in both Eurasia and North America at this time, but apparently not now migrants:
Insectivora: Erinaceidae; Soricidae
Lagomorpha: Leporidae
Rodentia: Ischyromyidae; Eomyidae
Carnivora: Hyaenodontidae; Procyonidae; Mustelidae; Felidae
Perissodactyla: Tapiridae (probable but not certain in Eurasia at this time); Amynodontidae; Rhinocerotidae
Artiodactyla: Anthracotheriidae

Middle and late Oligocene, the successive faunas of which are not markedly distinct and are characterized by moderate phyletic evolution more or less *in situ*, were times of minimal faunal interchange between Eurasia and North America. Quite possibly all the apparent migrants, or migrants of record, during this time had really migrated in the early Oligocene but have not yet been found in collections of that age. On the other hand the barriers between Eurasia and North America may never have been 100 per cent effective, and a certain amount of waif and stray, or sweepstakes, migration may well have occurred even at this time. Groups that had previously migrated and that were still present on both continents tended to drift apart and by the end of the Oligocene had generally developed quite distinct genera or somewhat higher taxonomic phyla in the two regions. Other groups previously common to the two now became extinct in one, *e.g.*, Brontotheriidae, Dichobunidae, Entelodontidae.

Other groups that had not as yet migrated (*e.g.*, Cervidae, Camelidae) or that were destined never to migrate (*e.g.*, Cainotheriidae, Merycoidodontidae) progressed and became even more distinctive. The general result was a strong decrease in faunal resemblance between Eurasia and North America, slow at first but by the end of the Oligocene so pronounced that the two continents then represented decidedly different mammalian faunal realms.

EARLY AND MIDDLE MIOCENE

Important migrants

Perhaps from Eurasia to North America:
- Carnivora: *Pachycynodon*; Amphicyoninae, *Amphicyon*; Lutrinae
- Proboscidea: Mammutidae, *Mammut* (*Miomastodon*)
- Perissodactyla: *Macrotherium*
- Artiodactyla: Cervidae, Palaeomerycinae

Perhaps from North America to Eurasia:
- Insectivora: Scalopinae? (very dubious)
- Rodentia: Castoroidinae
- Perissodactyla: Anchitheriinae, *Anchitherium*

Important nonmigrants

In Eurasia:
- Insectivora: Dimylidae
- Primates: Dryopithecidae
- Pholidota
- Rodentia: Gliridae
- Carnivora: Melinae; Viverridae
- Proboscidea: Gomphotheriidae; Deinotheriidae
- Perissodactyla: Paraceratheriinae; Dicerorhininae
- Artiodactyla: Suidae; Anthracotheriidae; Cainotheriidae: Muntiacinae; Lagomerycidae; Giraffidae; Bovidae

In North America:
- Rodentia: Aplodontidae; Mylagaulidae; Marmotini; Geomyidae; Heteromyidae
- Carnivora: Procyonidae (may just possibly have migrated at about this time).
- Perissodactyla: Equinae; Aceratheriinae
- Artiodactyla: Agriochoeridae; Merycoidodontidae; Camelidae; Hypertragulidae; Protoceratidae; Dromomerycinae; Antilocapridae

(There are also several groups in which there was earlier, or both earlier and later, migration but apparently none at this time.)

The extraordinary thing about interchange in the early and middle Miocene is its paucity. On the whole, the faunas of the two areas continued to evolve quite independently, as they had in the middle and late Oligocene, and yet it seems clear that migration was possible and that some did occur. The migrations of *Mammut* (*Miomastodon*), *Anchitherium*, and the Cervidae seem to be well dated within this time

span, and these are not likely to be waifs that migrated without a practicable, complete land route. It is, then, quite surprising that there is so little other evidence of migration until the late Miocene. The migration of the Cervidae is an event of the greatest importance for later faunal history and is an exception to the strong tendency for specialized artiodactyls not to migrate between these two continents.

LATE MIOCENE

Important migrants

Perhaps from Eurasia to North America:
- Insectivora: Erinaceinae? Crocidurinae? Talpinae? (All three are extremely dubious.)
- Carnivora: *Hemicyon*; *Pseudaelurus*; *Mustela* (?)
- Proboscidea: Gomphotheriidae, *Gomphotherium*, *Serridentinus*, Rhynchotheriinae, *Rhynchotherium*
- Perissodactyla: Teleoceratinae

Perhaps from North America to Eurasia:
- Rodentia: Castorinae; *Amblycastor*
- Carnivora: Borophaginae
- Perissodactyla: *Hypohippus* (perhaps migrated a little later)

Direction wholly dubious:
- Rodentia: Sciuridae, Sciurinae

Important nonmigrants

In Eurasia:
- Insectivora: Dimylidae
- Primates: Dyropithecidae
- Rodentia: Rhizomyidae; Gliridae
- Carnivora: Viverridae; Hyaenidae
- Proboscidea: Deinotheriidae
- Perissodactyla: Aceratheriinae; Dicerorhininae
- Artiodactyla: Suidae; Tragulidae; Muntiacinae; Lagomerycidae; Giraffidae; Bovidae

In North America:
- Rodentia: Mylagaulidae; Geomyidae, Heteromyidae
- Carnivora: Procyonidae? (If they did migrate, it was probably earlier than this.)
- Perissodactyla: Equinae
- Artiodactyla: Merycoidodontidae; Camelidae; Dromomerycinae; Antilocapridae

This is the most extensive faunal interchange between the early Oligocene and the latest Pliocene, but it is not very extensive. It grades into the early Pliocene (Pontian) interchange, which is of less intensity and of slightly different character, and the two together constitute a major episode in this history. Although imperfectly distinguished, the late Miocene and early Pliocene interchanges, as here nominally

recognized, do probably represent different waves or impulses of migration, the exact dating of which is much disputed. Insofar as it can be distinguished on present data, this late Miocene interchange is especially marked by the relative scarcity in it of perissodactyls or artiodactyls and by the extensive migration of the Proboscidea. Other migration at this time seems to have included only scattered genera or phyla of groups that had already shown a tendency to migrate.

EARLY PLIOCENE

Important migrants

Perhaps from Eurasia to North America:
Proboscidea: *Tetralophodon*; Platybelodontinae, *Platybelodon*
Perhaps from North America to Eurasia:
Rodentia: Aplodontidae
Perissodactyla: Equinae, *Hipparion*

Important nonmigrants

In Eurasia:
Primates: Lorisidae; Cercopithecidae; Dryopithecidae; Pongidae
Rodentia: Rhizomyidae; Gliridae; Muridae
Carnivora: Viverridae; Hyaenidae; Felinae
Tubulidentata: Orycteropodidae
Proboscidea: Elephantidae; Deinotheriidae
Hyracoidea: Procaviidae
Perissodactyla: Chalicotheriidae (now extinct in America and not reintroduced); Aceratheriinae; Rhinocerotinae; Dicerorhininae; Elasmotheriinae
Artiodactyla: Suidae; Anthracotheriidae (extinct in America and not reintroduced); Tragulidae; Muntiacinae; Cervinae; Odocoileinae; Giraffidae; Bovidae.
In North America:
Rodentia: Mylagaulidae; Geomyidae; Heteromyidae
Carnivora: Procyoninae
Artiodactyla: Merycoidodontidae; Camelidae; Protoceratidae; Dromomerycinae; Antilocapridae

The placing or the individuality of this particular interchange is made especially dubious by inconsistencies of record and by the highly disputed correlation and subdivision of this part of the time scale. The present arrangement, revised after consultation especially with McGrew and with Stirton but not endorsed in detail by either of them, tends to reduce the nominally early Pliocene interchange to a minimum and to refer much interchange that some authorities consider early Pliocene either to the previous or to the following subepoch. In any case, the interchange here called late Miocene was followed by further but, it seems, distinctly less extensive interchange of almost the same sort. It is not wholly clear whether this should be considered a weak new surge of migration or simply a tapering off of mi-

gration among stragglers of an intermigration around the Mio-Pliocene boundary. The whole movement is especially characterized by migration of Proboscidea from the Old World to the New and of Equidae in the reverse direction. This was followed by a falling off of migration and then by a new, more varied and intense series of migratory episodes that will be seen beginning in the middle Pliocene and culminating in the Pleistocene. In the late Miocene-early Pliocene, the artiodactyls again failed to migrate, and this becomes increasingly emphasized as more varied and more advanced types continue to become differentiated on both continents. The early Pliocene is, for instance, characterized by a tremendous expansion of bovids of many sorts in Eurasia, but none of these reached North America at this time, and few at any time.

MIDDLE PLIOCENE

Important migrants

Perhaps from Eurasia to North America:
  Carnivora: Ursidae, *Agriotherium*, *Indarctos*; Melinae; Mephitinae; *Machairodus*
Perhaps from North America to Eurasia:
  Rodentia: *Dipoides*; Microtinae; Zapodidae
Direction wholly uncertain:
  Carnivora: *Plesiogale*
  Perissodactyla: *Tapirus*

Important nonmigrants

In Eurasia:
  Insectivora: Erinaceidae (now or shortly extinct in North America)
  Primates: Cercopithecidae; Pongidae
  Rodentia: Rhizomyidae; Muridae; Gliridae; Dipodidae; Hystricidae
  Carnivora: Felinae; Viverridae; Hyaenidae
  Proboscidea: Elephantidae
  Perissodactyla: Chalicotheriidae; Rhinocerotidae
  Artiodactyla: Suidae; Anthracotheriidae; Hippopotamidae; Tragulidae; Muntiacinae; Cervinae; Odocoileinae; Giraffidae; Bovidae
In North America:
  Edentata: Megalonychidae
  Rodentia: Geomyidae; Heteromyidae
  Carnivora: Procyoninae
  Artiodactyla: Tayasuidae; Merycoidodontidae; Camelidae; Antilocapridae

The middle Pliocene, as here defined, saw a distinct new upswing in intermigration. Almost all the animals known to have been involved were rodents or carnivores, and there is a singular lack of herbivores. Even the case of *Tapirus* is very doubtful as to dating, and this genus may not really have migrated at this time. This episode may be viewed as the last of the distinctively Tertiary intermigrations (except for the doubtful and conservative genus *Tapirus*, no living genus seems to be involved),

or as the beginning of the upswing of migration that was to culminate in the Pleistocene.

LATE PLIOCENE

Important migrants

Perhaps from Eurasia to North America:
- Insectivora: *Sorex*
- Lagomorpha: Leporinae?
- Carnivora: *Martes*; *Lutra*; Felinae, *Panthera*; Hyaenidae
- Proboscidea: Anancinae
- Artiodactyla: Cervinae, *Cervus*; Odocoileinae

Perhaps from North America to Eurasia:
- Lagomorpha: *Hypolagus*
- Rodentia: *Citellus*; *Tamias* (time and direction uncertain); *Castor*
- Perissodactyla: *Equus* (*sensu lato*)

Direction wholly dubious:
- Rodentia: *Mimomys*
- Carnivora: *Canis*

Important nonmigrants

Essentially the same as the Pleistocene nonmigrants plus, somewhat doubtfully in most cases, most of the forms that did migrate in the Pleistocene and not in the Pliocene.

This interchange is, in a sense, a continuation of that beginning in the middle Pliocene, but it is distinctly more varied and more modern. It culminated and was most clearly evident in the American Blancan, European Villafranchian or Astian, and Chinese Sanmenian or Nihowan—stages marking the Plio-Pleistocene transition and referred by some authorities to the earlier and by some to the later epoch. In any case it is the beginning of an interchange of Pleistocene type, and its separation from the Pleistocene interchange is in part artificial. There was probably more or less continuous interchange from late Pliocene through mid-Pleistocene. Members of the microfauna, particularly, credited to the Pleistocene may well have migrated in the Pliocene, as here defined, and this is a possibility for other groups. There was also, however, a distinctly Pleistocene wave, evidenced, for instance, by the bovids. The late Pliocene and perhaps to less extent the Pleistocene migrations are characterized by the interchange of genera, most of which still survive, within families already common to the two continents.

PLEISTOCENE

Important migrants

Perhaps from Eurasia:
- Lagomorpha: *Ochotona*; *Lepus*

Rodentia: *Sciurus*; *Petaurista*; *Lagurus*. (Direction is very uncertain for all of these.)
Carnivora: *Ursus*; *Gulo*; *Felis* (perhaps migrated earlier)
Proboscidea: Elephantidae, *Mammuthus*
Perissodactyla: *Equus*? (according to McGrew; the orthodox view is that *Equus* migrated in Blancan-Villafranchian time, as listed above, and in the opposite direction); *Tapirus*? (migration may have been much earlier and in that case possibly in the opposite direction)
Artiodactyla: *Alce*; *Rangifer*; Bovidae, *Saiga*, *Bos*, *Bison*, *Ovis*; Ovibovinae
Perhaps from North America:
Rodentia: *Marmota*; *Dicrostonyx*; *Lemmus*; *Clethrionomys*; *Pitymys*; *Microtus*; *Zapus*. (Direction is very uncertain for all of these.)
Carnivora: *Vulpes*
Artiodactyla: Camelidae

Important nonmigrants

In Eurasia:
Insectivora: Erinaceidae (extinct in America and not reintroduced); Crocidurinae (same); Talpinae (same); Desmaninae
Primates: Lorisidae; Cercopithecidae; Pongidae; Hominidae (migrated in late Pleistocene, after the essential completion of the Pleistocene migrations)
Pholidota: Manidae
Rodentia: Spalacidae; Rhizomyidae; Muridae; Gliridae; Sicistinae; Dipodidae; Hystricidae
Carnivora: Viverridae; Hyaenidae
Perissodactyla: Chalicotheriidae (all migration was earlier); Rhinocerotidae (all migration was earlier)
Artiodactyla: Suidae; Hippopotamidae; Tragulidae; Giraffidae; most Bovidae
In North America:
Edentata: Megalonychidae; Megatheriidae; Mylodontidae; Dasypodidae; Glyptodontidae
Rodentia: Geomyidae; Heteromyidae; Erethizontidae; Hydrochoeridae
Carnivora: Procyonidae (migration was much earlier)
Artiodactyla: Tayassuidae (any migration was earlier); Antilocapridae

This was a very pronounced interchange, the most extensive and intensive that has occurred with the probable exception of that in the early Eocene. It also seems to have included more variety and a more nearly balanced type of fauna than any interchange since the early Eocene, although this may be due in part, at least, to imperfect knowledge of the intervening migrations. In spite of these facts, it involved only a minor part of the faunas of the two continents as a whole and had relatively little effect on their gross composition. Most of the migrants were merely new but ecologically closely similar forms of groups already common to both faunas. One really striking novelty reached Eurasia at this time, or perhaps a little earlier—the Camelidae—, but this group never became very important in the Eurasian fauna.

Migrants from Eurasia were more important in the North American fauna. The mammoths, although now extinct, were abundant in the Pleistocene and ecologically rather distinct from the mastodons that had reached there long before. The modernized types of deer and especially the bovids had an even more profound influence, and this persists today. The highly selective nature of the interchange is emphasized by the fact that even in groups that did have some migration, like the bovids and the microtines, the actual migrants are only a very small minority of the forms existing in one area or the other.

GENERAL SUMMARY

In the early Eocene, the migrating forms apparently constituted a major part of the continental faunas. This was never again true, and, although it cannot be conclusively demonstrated, there seems to have been a progressive tendency for successive migrations to affect smaller and smaller fractions of the faunas. There is a definite and demonstrable tendency for successive migrations to introduce progressively less distinctive types of mammals into the continents to which they migrated. In the early Tertiary, mammals appearing on one continent or the other as a result of migration represent a large proportion of higher taxonomic groups, orders, families, or subfamilies, new to that continent. This is particularly true of the early Eocene, late Eocene, and early Oligocene interchanges. Thereafter the interchanges are increasingly confined to genera, or minor phyla of more or less tribal or generic scope, within groups already common to the two regions. In correlation with this phenomenon, it appears that the great majority of supergeneric groups that arose on one continent after the early Tertiary failed to migrate to the other. A broad faunal type of general Holarctic stamp was established by migration during and before the early Oligocene, intermingled on each continent with increasingly typical Eurasian or North American elements, and later migration was nearly confined to groups that fitted in with this Holarctic element or stratum.

Zoologically, the early Eocene interchange involved members of all the orders and most of the families that were then abundant and conspicuous. Important exceptions were the palaeotheres and lophiodonts in Europe. Apparent American exceptions are rather dubious. Later interchanges involve continual and evidently quite complex migrations of several types each of lagomorphs, rodents, and carnivores. Most of the distinctive types of perissodactyls migrated as or soon after they arose, and so, in the later Tertiary, did the proboscideans. During the mid-Tertiary, particularly, very few artiodactyls migrated, and when noticeable artiodactyl migration did occur in the late Tertiary and Pleistocene this involved only a very small minority of the many distinctive types peculiar to each region.

Direction of migration is so uncertain in most cases that generalization concerning it must be taken with great caution. The directions of the early Eocene migrations are unknown, even in a tentative way. All later faunal interchanges evidently involved migration in both directions, as would be expected. In the late Eocene, there is some slight suggestion that migration was more from North America to Eurasia than in the opposite direction, but this is quite uncertain, especially in view of the deficiency of knowledge of the Asiatic Eocene. Thereafter the evidence sug-

gests, for each climax or major episode of interchange, that more groups migrated from Eurasia to North America than in the opposite direction. This, too, is not certainly established, but the consistency of the evidence for each of the major interchanges here distinguished gives weight to this conclusion.

This question of predominant direction of migration has interesting ramifications and bearings on evolutionary theory worth mentioning even though the discussion here becomes frankly speculative. It seems to be true that groups that have already migrated more broadly or that have been associated with more numerous migrants are more likely to migrate when new opportunity arises. This is strikingly exemplified by the North American-South American interchange. Many more groups migrated from North America to South America than in the reverse direction. Subsequent extinction also affected the groups of different geographic origin differently; many more South American than North American groups became extinct. (See data in Simpson, 1940.) Some of the North American groups were migrants from Eurasia, and all had been involved directly or indirectly in the faunal interchanges with that continent, if only by having survived irruptions of competitors and other crises involved in so much population change. The South American groups were all old autochthones that had been living in virtual isolation for a long time. It is inferred that this difference in history had involved selection in North America favoring groups that were better able to meet changing conditions, reflected both in their invasion of new environment and in their greater survival during a time of widespread extinction. Contrary to some opinions, the South American animals as a whole do not seem to me to have been particularly less progressive or more primitive in morphological advance and adaptation. The difference must rather have been in physiology, in balance of genetic systems, perhaps also in population structure, adding up to different degrees of ecological flexibility and adaptive efficiency.

In the case of North America and Eurasia, the North American mammals did not develop in isolation like those of South America, but their faunal history was more tranquil than that in holarctic Eurasia where there were not only internal population movements on a larger scale but also faunal interchanges with two major faunal regions in addition to North America. The Eurasian temperate zone reservoir from which Bering Straits migrants were drawn was also much larger than the corresponding region in North America, and it was more frequently invaded by aggressive newcomers (*e.g.*, from Africa and southern Asia). It would thus be expected that ability to migrate and to survive under changing conditions would be selected far more rigorously in Eurasia than in North America. It would follow that the predominant direction of migration would be from Eurasia to North America and that, wherever they were at the time, groups of Eurasian origin would tend to survive longer than those of North American origin. The available facts, inconclusive in themselves, appear to agree with these theoretical considerations.

SELECTIVITY OF MIGRATION

A faunal interchange between two regions may theoretically vary, and may be seen to vary in fact in various instances, from an essentially complete mixing of the two faunas to the passage of a single species or subspecies from one region to the other.

The interchanges here under discussion do not belong to either extreme. The early Eocene migrations, wherever they came from, did involve most, but not all, of the mammalian groups of both continents. At that time there can hardly have been any strongly selective barrier, and the connection suggested is a corridor rather than a filter. The later interchanges were all highly selective, but each involved movements in both directions by mammals of several orders and many families or lesser units. They thus involve neither the free mixture that would be promoted by supposed transoceanic continents (or the contact phases of continental drift) nor the waif dispersal of sweepstakes routes, but are evidently the result of dispersal across selective filter bridges. (*See* Simpson, 1940.)

The selective action of such a migration route must depend largely on three intimately related but, on the whole, separable factors. There is, first, a climatic or broadly environmental factor. In the continents in question, major faunal zoning tends to be latitudinal, by climatic zones. The migration routes involved are inferred to have run approximately east and west and to have been relatively narrow, at least in the middle and later Tertiary, so that they would lie within a single climatic zone. The physical position of the route would, then, exclude many mammals from migrating over it; mammals confined to faunal zones against which the route did not abut were necessarily nonmigrants.

The second selective factor is more narrowly environmental, or related to particular habitats, and involves the ecological conditions on the bridge and in the zones around its two abutments. Animals narrowly adapted for desert life, for instance, will not ordinarily migrate along a route that is heavily forested, nor will grazing animals ordinarily migrate where there is no grass.[7]

A third and even more complex factor arises from intra- and intergroup competition. With rare exceptions, land mammals do not migrate in the sense that a population as such leaves one area and moves to another. Although application of the word "migration" as in this paper is a convenience sanctioned by usage, the actual phenomenon concerned is more accurately described as expansion when applied to such major movements of land mammals as are here considered. Overpopulation and intense intragroup competition are determinants for such expansion. Even when unfavorable environmental change is involved, the animals do not deliberately seek more favorable conditions on another continent and mammals usually will not migrate unless, under existing conditions, the territory already occupied is overpopulated. As a rule, the migrants belong to abundant and expanding groups. Waning groups and those in which the population is in equilibrium with its food supply seldom migrate even though there is full physical opportunity for them to do so.[8]

The other side of this factor of competition is that animals are rarely able to migrate into regions where closely competitive types are already established unless they have definite adaptive advantages over those competitors. When two competing

[7] Stirton (personal communication) comments on this that animals do sometimes wander across areas quite unsuited to them and so may cross ecologic barriers and become established in suitable areas beyond these, even if not impelled by population pressure. The possibility cannot be denied, but most mammals exhibit such strong attachment for particular ecological situations and for their home ranges that I think such events must be very exceptional.

[8] Mayr (personal communication) points out that in such cases there is, strictly speaking, no opportunity to migrate because the lack of a population surplus indicates unfavorable ecologic conditions, and these unfavorable conditions are in themselves an effective barrier to migration.

groups come into contact on or near a potential migration route and one is adaptively superior to the other, the superior group will migrate, and the inferior group will not. As a secondary result, the inferior group will usually become extinct in due course, although this result may be long delayed. Thus migrant forms, other things being equal, are either those adaptively superior to prospective competitors in the area of immigration or are of adaptive types not previously present in that area. Conversely, other things being equal, this biotic factor, not directly related to the migration route as such, will supplement the filtering action of the route by preventing the migration of inferior competitive types.

Application of these principles to the Eurasian-North American faunas involves much inference and some speculation but is nevertheless highly suggestive.

Little can be said of the climatic position of the early Eocene migration route. The known faunas are of limited range in latitude, and all occur in the central parts of what is now the temperate zone. The route must have been broadly accessible from that zone and was apparently less selective than any later line of migration.

Known late Eocene and early Oligocene faunas are also poorly representative of different latitudes. The migrants are still rather broadly distributed among the faunas of middle latitudes, but there is a much stronger selective effect which suggests that the route may not have been in that zone. Comparison of the most northern and most southern known faunas of this age in North America does not reveal any clear tendency for one to include more migrant groups than the other, but there is no great difference in latitude between the known faunas, and a real zoning of migrants may have occurred without being revealed by the data in hand. In Asia, as discussed in more detail later, there is some evidence that faunal zoning between the south (Pondaung fauna of Burma) and central (Shara Murun of Mongolia) parts of the continent had begun (Colbert, 1938), and the southern fauna includes one important nonmigrant group, Primates, apparently absent farther north. The zoning was probably less distinct than it was to become in the Miocene, and it is probable but not fully certain that the Mongolian fauna is closer to the North American than is the Burmese fauna. The most striking nonmigrants at these times included some groups destined to be long- and farranging on their own continents and yet never to migrate between the two regions. A strictly geographic explanation of failure to migrate, involving physical barriers, may apply to many of them, but it is uncertain whether this is a sufficient explanation. In many cases the filter action must have been more narrowly ecological.

Before the Miocene, a climatic factor is suggested but not demonstrated by what is now known. By late Miocene time, however, a climatic zonal factor in the selectivity of migration can be definitely inferred, and this became more and more evident in the Pliocene and Pleistocene. In America we still know little about faunal zones in the Miocene but we have some hint of zoning in the Pliocene and have extensive data in the Pleistocene, although these data have not been conveniently digested and compiled from this point of view. There is no real indication as to the climatic preference or tolerance of some of the nonmigrants, like the oreodonts. In other cases there is some indication, and in these cases all the groups known to tolerate relatively cold climates did migrate sooner or later, and none of

the animals known to be largely or wholly confined to warm climates did migrate. From the evidence of their recent relatives, these American groups have members that thrive in cool or cold climates: Castoridae, Zapodidae, Aplodontidae, Microtinae, Marmotini, Caninae, Equidae, Camelidae. All migrated to Eurasia in the later Cenozoic.

Association of camels with the Sahara has induced in the minds of some students a feeling that these are warm-climate animals. In fact the wild camels of both the Old World and the New live best or only in cold temperate regions, and it is a reasonable assumption that this was true of the forms that migrated between the two areas. On the other hand, the long delay in their migration may have been caused by their slowness to develop cold-climate adaptations, although this is frankly speculative. Some equids are well adapted to warm and even to hot climates, but they include species and races best suited to cold temperate regions.

These American groups are characteristic of warm climates and are rare or absent in cold climates: Didelphidae, Procyonidae, Geomyidae, Heteromyidae, many cricetines (although there are northern lines, some of which evidently came from Eurasia, and this was perhaps the history of the remote ancestry), Hydrochoeridae, and all the varied Edentata. None of these migrated to Eurasia in the Miocene or later.[9]

Erethizon is now largely a cold temperate animal in North America and did not migrate to Eurasia. It may be an exception to these generalizations, but this is not necessarily so. It reached North America through the Tropics, and its ancestry was probably tropical. Its history here has probably been one of increasing adaptation to colder climates. It may not have reached a far northern bridge early enough and in sufficient numbers to make the trek to Eurasia.

The Antilocapridae are a doubtful group in this respect. In recent times, *Antilocapra* has ranged into cool temperate regions, but it is more characteristic of temperate to warm temperate latitudes. The abundant later Tertiary antilocaprids may have been kept out of Eurasia by their intolerance for cold. This may have been a factor, too, in their great reduction in variety around the end of the Tertiary, when the climate became generally cooler. Another possible factor is the establishment in Asia of ecologically similar bovids. Again, the immigration of bovids into North America may have been a factor in antilocaprid decline although, perhaps significantly, these immigrants did not include the bovids most similar to the antilocaprids and did not effect total extinction of the antilocaprids. A third possible factor (and it is probable that all these cases involve the interaction of several factors) is more narrowly environmental: the preference of antilocaprids and analogous bovids for broad, open steppes, which probably did not exist continuously across the Bering bridge.

Climatic selectivity is still more apparent when viewed from the Eurasian side. By Miocene times, at least, a climatic faunal zoning was established in Asia. This became increasingly marked in the later Cenozoic, and the sharpness of the separation was intensified by the rise of east-west physiographic barriers. It culminated in the present distinction of the Oriental and Palaearctic regions. In Europe the zoning is

[9] It has been suggested (Colbert, personal communication) that the procyonids are an exception if the pandas belong in that family, as is probable. I believe, however, that the pandas are more likely to be derivatives of Oligocene Eurasiatic procyonids than of a later migrant line from North America. Moreover, the procyonids as a whole seem to be somewhat more tolerant of cold habitats than the other groups mentioned.

less clear in the fossil faunas and is much less pronounced today, but there is such zoning and apparently has been since the Miocene and probably still earlier.

There is little direct evidence as to climatic preferences of the Miocene migrants from Eurasia except that most of them belong to groups known to have developed some cold-climate lines: several groups of insectivores (doubtful migrants), Canidae, Proboscidea, rhinoceroses, and cervids. Among the most conspicuous migrants were the Proboscidea, and within this group there is a curious lag and selectivity. Most of the phyla that did migrate to America arose some time before they made this expansion, and some abundant phyla failed to make it. Although this is, in part, speculative, a reasonable explanation would be that the Proboscidea as a whole were of subtropical to tropical origin and primary deployment and that only certain offshoots became rather slowly adapted to temperate and finally to boreal conditions. It was these lines that eventually migrated to America when they had finally developed sufficient tolerance to cold to cross a far northern bridge.

The most striking nonmigrants in the Miocene, and for most of them also in the Pliocene and Pleistocene, were the Primates, Rhizomyidae and Gliridae, Viverridae and Hyaenidae, Deinotheriidae, Dicerorhininae, Suidae, late Anthracotheriidae (and, later, their descendants the Hippopotamidae), Tragulidae, Muntiacinae, Lagomerycidae, Giraffidae, and Bovidae. There is good evidence that these were all mainly warm-climate animals and are not likely to have ranged in any force into a cold temperate or boreal environment. Most of them are, for instance, especially typical of the south Asiatic fossil faunas and are either absent or decidedly less varied and less abundant in contemporaneous central Asiatic faunas, which nevertheless probably represent a more tempered climate than prevailed on the bridge to America. Except for some bovids and one suid, the modern representatives of surviving groups are confined to warm temperate to tropical regions. This evident lack of adaptation for cold climates is the one thing that these nonmigrants have in common. The evidence, although negative, is quite impelling in favor of a relatively cold-climate migration route.

The early Pliocene evidence re-enforces this conclusion. The migrants are similar and now include also the Ursidae, a group most typical of cold temperate to boreal environments, although it did range into the Siwaliks. To the list of striking nonmigrants are added the Muridae, Orycteropodidae, and stegodonts. These, again, are plainly groups that evolved in a subtropical to tropical environment and that never penetrated far into the cold temperate zone, except for a few later strays among the Muridae.

Late Pliocene and Pleistocene migrants include in the most significant way just those genera or other groups that thrive in the colder continental areas. Whatever may be said of earlier migrations, there has never been any serious question that this last great series of interchanges involved cold temperate to boreal faunas. Some groups, however, do call for special comment. The Hyaenidae are mainly a warm-climate group, and their failure to migrate in the early Pliocene, when they were very abundant in Eurasia, has been explained on that basis. Nevertheless one specimen of a probable hyaenid has been found in North America (Stirton and Christian, 1940). In the late Pliocene and Pleistocene they penetrated well north in China, and this

mainly warm-climate group probably developed a cold-climate phylum able to reach and cross a sub-Arctic bridge. Their great rarity in North America and failure to survive there are doubtless significant.

The mainly southern stegodonts failed to cross to America, but the elephantids did reach there in the form of *Mammuthus*,[10] the group that was predominantly and typically northern in Eurasia.

The extremely varied and mainly southern bovids also finally reached America in the Pleistocene. The picture of their development in Asia is that of a great swarm of forms in the tropical and subtropical centers of their evolution, with more and more attenuated representation in passing into colder alpine and northern regions, to which a few quite diverse lines became adapted. (On the late Tertiary flowering of the bovids in the Oriental region and on the history of the group in general, *see* especially Pilgrim, 1939.) The migrants to America were drawn exclusively from these cold-climate lines: the tundra-adapted Ovibovinae, the temperate to cold-steppe *Bison*, and two alpine forms *Oreamnos* (exact ancestry unknown but related to the alpine chamois, goral, and serow) and *Ovis*. Two more cold-steppe and cold-desert forms, the yak and the saiga antelope, reached Alaska (Frick, 1937) but are not known farther south and certainly did not become abundant and widespread in America. Their failure to become integrated in the American fauna was thus not due to inability to cross the bridge but must have been ecological. In fact each is quite sharply adapted to a particular type of environment which is not well represented in North America, and spreading to what would be for them marginal environments would be impeded by the presence of animals, such as the bison, already well adapted to those environments.

The examples of the yak and saiga antelope also suggest that the Tertiary history, as we are compelled to follow it in middle latitudes only, is affected by a double selective influence of climate. The migrants that we find and know are those not only able to cross a bridge located in all probability in far northern latitudes (*see* later discussions in this paper) but also able, after making this crossing, to descend into the middle latitudes of the Eurasian and North American Tertiary mammalian fossil fields. In the earlier Tertiary the climatic differences involved were not great, and selectivity would presumably be less marked, as the record suggests that it was, in fact. Selectivity by this double factor, requiring tolerance to cold but not exclusive adaptation to a boreal climate, would become increasingly stringent in the later Tertiary. In the Pleistocene it would again be less, as viewed in the middle latitudes, because of the condition, reversed from the early Tertiary, that boreal climates extended into those latitudes. (In the Pleistocene we also know northern mammals.) Thus, if *strictly* cold-climate animals, such as the muskoxen, crossed in the Pliocene, we are unaware of that fact because the middle latitudes were not suitable for them. Such groups, including the muskoxen, reached these latitudes in the Pleistocene and are known as fossils at that time both here and in the north and are still living in the north.

Such examples indicate another complication that must be kept in mind, especially

[10] Under this name I place all of Osborn's slightly distinguished genera of American mammoths, as well as the closely related Old World forms.

in considering the later Cenozoic part of the history. The migration of record, when the record is in middle latitudes, may have been a movement southward on each continent of circumpolar groups and not an intercontinental east-west movement. The circumpolar distribution in such cases would, however, be the result of earlier eastward or westward migration.

A great part of the selectivity of faunal interchange in and after the mid-Tertiary, at least, and particularly as we know the faunas, can be accounted for by the climatic factor. The migration route clearly led through a cold area and filtered out all animals that could not survive in a more or less rigorous climate. It is doubtful whether this factor applied to the early Eocene migration (or to Paleocene migrations, about which so little is known). It may have applied in the late Eocene and Oligocene, if so probably to less degree than later, but we can infer little about the climatic preferences of the animals of those times. As has been noted, it is also probable, on other evidence such as that of paleobotany (*e.g.*, Chaney, 1940), that cold climates in those epochs were less rigorous and covered less of the continents than in the later Tertiary, so that even a far northern bridge would then be less selective on a climatic basis.

In any event, and contrary to what seems to be a widespread impression (*e.g.*, J. W. Gregory, 1930), there is no evidence from the mammals that any truly tropical or subtropical animals ever migrated between Eurasia and North America, and it is even dubious whether any specifically warm temperate groups made this journey. The tapirs probably are the most nearly impressive evidence against this conclusion. They are rare fossils, and their history is poorly known, but they may have been involved in several Tertiary migrations, most recently perhaps from North America to Eurasia in the Pliocene. Recent tapirs are mainly tropical. Although rare, Tertiary and Pleistocene tapirs are rather widespread and were less exclusively tropical, but still perhaps more warm than cool temperate in their main range. On the other hand the recent South American paramo tapir, although tropical as to latitude, lives in a very cold environment essentially like that of the Arctic tundra. This is in some respects the most primitive of the living species, and it is quite possible that it retains the climatic adaptation of the ancestral intercontinental migrants.

The climatic factor is here stressed as a selective influence on Eurasian-North American intermigration, but it is not supposed that it acted alone or that it provides a complete explanation of the screening of migrants in this case. The process was certainly complex, and no single or simple explanation can be expected. Although I believe that the preceding discussion establishes climatic zoning as one of the factors involved, and as a truly important factor, there are possible objections to this view[11], and other, alternative or concomitant factors must also be sought.

It has been urged against the present views that climatic zoning of mammals during the Tertiary is not established beyond all possible doubt by the available evidence. Some, at least, of the apparent differences between northern and southern faunas in the Miocene of Asia, for instance, could be due to accidents of collecting or to inaccuracy of correlation. It is nevertheless apparent that what evidence there is

[11] Among the critics of this paper in manuscript, most accepted the importance of climatic zoning to the extent that this is maintained in the foregoing discussion, but Stirton strongly dissented, and he tends to consider this factor as relatively unimportant or negligible during the Tertiary.

does support the hypothesis of climatic zoning. Insofar as I know, there is no good evidence against this hypothesis, which is so much more probable, *a priori*, that the burden of proof is on the other side. Under any theory, the astronomical relationships of earth and sun cannot have been very different during the Tertiary from recent conditions, and these relationships make some degree of climatic zoning inevitable. If the climates, themselves, were zonal it seems to me extremely probable that the mammals were, also.

There is, indeed, evidence, especially from paleobotany, that climatic zoning was less sharp in the early Tertiary than it is today and that there was then less difference between arctic and equatorial climates. This generally equable condition apparently changed slowly during the Tertiary and then more rapidly to the climax of zoning in the Pleistocene. But the botanical evidence (*e.g.*, Chaney, 1940) is that there was some climatic zoning even in the Eocene, and these probabilities as to climate tend rather to support than to oppose the importance of climate as a selective factor in mammalian migration in the northern hemisphere. The intermigration was relatively unselective in the early Tertiary and seems to have become progressively more selective during the later Tertiary and most selective in the Pleistocene, a sequence too nearly parallel with the probable progress of climatic zoning to be dismissed as purely coincidental.

Another objection (particularly stressed by Stirton) is that we do not really know the climatic preferences or adaptations of Tertiary mammals, which may have been quite different from those of their recent allies. This is true of any single case and may account for puzzling apparent exceptions. It would, however, be great excess of caution to conclude that we cannot, therefore, consider possible climatic selection in Tertiary mammals, and it would be quite illogical to conclude that climate had no important effect because we do not know the precise climatic status of Tertiary mammals. Again, there is a question of burden of proof. If a living group is definitely, exclusively, or predominantly distributed in warm climates, there is surely some probability (although never a certainty and always open to exception) that this has a historical basis and was also true of the Tertiary ancestors of that group. If then we find, as we do, that many or most of the nonmigrants in times when climatic zoning was probably becoming more definite do belong to groups now characteristic of warm climates, it seems reasonable to conclude that the fossil forms also favored warm climates and that this influenced their nonmigrant status. The argument is not circular, but reinforcing.

It is probable that any warm-climate mammalian group can become adapted to colder climates. This has certainly happened in some cases (*e.g.*, the Siberian tiger), and the potentiality can hardly be denied in any case. To argue from this, however, that all groups are potential migrants over a cold-climate route, that climate has no effect on selective migration, or that we cannot infer the nature of that effect seems, again, quite unjustified. Although any warm-climate group might invade a cold climate, most of them do not. The actual barrier may be considered biotic rather than climatic. In many or most cases failure to spread from warm to cold climates may be caused by the presence, in the colder region, of ecologically competing groups already adapted to that climate and therefore at an advantage there. This

exemplifies the fact that climate, like any other factor, is part of a complex and does not operate alone, but it does not alter the fact that climate is in such a situation an essential substrate or correlate.

In fact this possibility that certain lines of descent from warm-climate groups may become adapted to cold climates only reinforces the conclusion that (cool to) cold climate on the migration route between Eurasia and North America did have an important selective influence. It was, for instance, precisely the few cold-adapted lines of the predominantly warmth-adapted Bovidae that migrated along this route. In view of the general picture, it is even possible that climatic selection of migrants was more stringent than could be inferred from recent animals alone and that the exceptional failure of supposedly cold-climate groups to migrate was caused by the fossil forms in question belonging, in fact, to warmth-adapted lines, or, conversely, with respect to supposedly warm-climate groups that did, as rare exceptions, migrate. We are not justified in assuming this explanation in individual cases, but the possibility suggests that the real influence of climatic zoning may well have been greater rather than less than is inferred from the record.

There are, indeed, some long-time nonmigrants to which the climatic filter theory may not apply at all, although some climatic influence cannot be wholly ruled out. It is hard to see why none of the vast herds of oreodonts reached Asia, especially during the early and mid-Tertiary when the climatic filter was presumably less effective. The long delay in camelid and bovid migration is also striking in this connection, although a climatic factor was clearly involved for the bovids, at least. In fact the relative rarity of artiodactyl interchange, in general, seems unlikely to be purely climatic although it may be largely so. It may be surmised that, once divergent artiodactyl groups had developed in the two regions, they were ecologically so nearly analogous in the two and so well adapted locally in each that the competitive factor operated strongly to impede interchange. The migrants were not, then, all the forms that became geographically eligible by reaching the climatic zone of the migration route, but only the few among these that were also rapidly increasing in population and ecologically different from or superior to their ecological analogues or vicars on the other continent.

The total filter effect was certainly both climatic and ecological, with the importance of one or the other factor varying in different cases.

On a smaller scale, there remain puzzling points like the failure of the elasmotheres and woolly rhinoceroses to migrate to America in spite of the fact that they seem to have been abundant members of the biocenosis from which most of the migrants were drawn and to have had no prospective competitors in America any closer than those with which they were successfully coping in Asia. For this and a few similar causes we can now only plead ignorance.

Closer ecological analysis, one of the important subjects for future research, is needed to determine more exactly the local environmental conditions on and around the migration route. From the considerable variety of animals involved in each interchange, it is clear that these conditions cannot have been highly specific. A large percentage of the migrants would seem to have been at home in wooded plains, and practically all of them would be accommodated if there were also frequent glades

or occasional savannas. Specialized desert or dry steppe forms are not recognized among the migrants except for the unsuccessful saiga antelope. Two alpine types migrated in the Pleistocene (or late Pliocene), but associated Asiatic alpine animals did not accompany them, and these particular animals (mountain sheep and "goat"), would not be impeded by hilly, or even flat, country if the climate were alpine or boreal.

TIMES OF INTERCONTINENTAL CONNECTIONS

GENERAL CONSIDERATIONS

From time to time some strays may have crossed a sea barrier between Eurasia and North America, but major faunal interchanges such as those here discussed require land migration routes. With the exception of the early Eocene connection, which may have been a corridor, they all meet the criteria that I have elsewhere suggested for inference of the existence of a filter bridge (Simpson, 1940). Explicitly, each interchange involves only a selected part of the faunas, but it involves assorted and more or less integrated faunules, with several or numerous different sorts of animals, and in each interchange migration occurred in both directions. It now remains to consider more particularly when these bridges existed and where they were.

It is basic that a time of definite and extensive faunal interchange establishes the existence of a bridge at the beginning of, if not entirely during, the observed time of the interchange. It is much more difficult to say when the bridge did not exist. It has been assumed that falling off in the interchange indicates breaking of the connection, but this is not necessarily true. After the first waves of migration, an equilibrium will tend to be established, and interchange may virtually cease even though a route for it persists. For instance there has evidently been little significant migration across the Panamanian bridge since middle or perhaps early Pleistocene time, because the groups apt to make that migration all did so quite soon after the bridge arose.[12]

There was no time during the Tertiary when one can say certainly that there was no migration whatever between Eurasia and North America. Times of relatively little apparent migration could represent complete absence of interchange, the first records for these times being belated discoveries of earlier migrants, or waif dispersal after disappearance of the bridge, or casual fluctuations across a bridge between two faunas in essential equilibrium. When such a time of low interchange is followed by an intense interchange, this may be taken as evidence that the bridge had been interrupted and that its restoration was the stimulus for new migration. But this, too, fails to be wholly conclusive. The mere rise of a bridge is not always and necessarily a sufficient condition for intensified interchange, nor is it the only possible stimulus for such an episode. The factors involved in expansion of this sort may be very complex. They may, and probable do as a rule, include such elements as population movements within each continent and relations with other more remote regions like South America in the New World and Africa in the Old.

Progressive faunal divergence is also evidence for absence of a land connection,

[12] For certain groups the bridge may have been effectively closed by changing ecologic conditions, *e.g.*, growth of rain forest.

but this, again, is inconclusive. When the bridge is localized in one faunal zone, which has evidently been the usual situation, considerable divergence may occur in other zones. For most of this history we have few or no fossils from the immediate areas whence the migrants were probably drawn. We have to try to infer what happened on and around the bridge from the effect on areas usually far distant, and this indirect evidence obviously cannot always be taken at full face value.

No attempt will be made to review previous opinions as to the time or place of each land connection. Older views were summarized in considerable detail by Arldt (1919–1922), and some more recent views are given, for instance, by Joleaud (1939) and by Furon (1941).[13] It is, however, fair to say that too little attention has hitherto been given to the difficulties pointed out above, and that some of the literature on this subject has represented the rashest sort of jumping at conclusions from scanty and misunderstood evidence. (*See*, for instance, some specific instances reviewed in Simpson, 1943.) In spite of these discouraging precedents and of the many uncertainties involved, a review of the probabilities as they now appear to me will be attempted.

PALEOCENE

Some connection between Eurasia and North America certainly existed between the Cretaceous and the Eocene, but knowledge of Paleocene mammals in Eurasia is so deficient that this cannot be localized either in time or in space.

EOCENE

Some part of Eurasia was connected with North America at the beginning of the Eocene. (The position of the connection will be discussed later.) The sharp drop in migration thereafter, the pronounced succeeding divergence of faunas in the two hemispheres, and the apparently abrupt later beginning of new interchange all suggest that this connection was broken before the end of the early Eocene and remained so through the middle Eocene. Another connection at the same or a different location was established at about the beginning of the late Eocene.

OLIGOCENE

There was a connection at the beginning of the Oligocene, and this may have lasted throughout the early Oligocene. There is no direct evidence that the connection had been broken after the late Eocene migration, but the distinct new surge of migration in the lower Oligocene, as well as the different nature of the animals involved, would seem to suggest either this or, with less probability, that the Oligocene bridge represented a new connection tapping a different faunal region. It is, however, also possible and perhaps most probable that the new surge of migration was an indirect result of internal movements in Eurasia. Migration declined very sharply in the middle Oligocene and still more in the late Oligocene. This suggests that the connection was broken then, but the evidence is not entirely clear. Faunal divergence during this time was only moderate, on a far smaller order of magnitude than that during the fairly well established Eocene separation, and it was not, like

[13] These works are cited as examples of the literature, not as authorities on the facts. All three seem to me highly unreliable.

that Eocene break, followed by intense interchange when connection was re-established (if it had been broken).

MIOCENE

Early Miocene conditions are rather puzzling. There is enough evidence of migration to suggest that a route did exist, but the apparent amount of interchange is far less than would be expected after the Oligocene minimum, and except for the migrant groups, themselves, faunal divergence continued. The early Miocene Eurasian and North American mammalian faunas as now known are actually less similar than those of the late Oligocene, in spite of the evidence that there was practically no late Oligocene migration and that there was some in the early Miocene. All this suggests that there was a connection in the early Miocene but that it was quite transitory, incomplete, or involved unusually sharply defined and rather peculiar geographic and ecological conditions. In the middle Miocene there was also relatively little interchange, but more than in the early Miocene, and the preceding gross faunal divergence was checked and the trend reversed. The suggestion is that the early Miocene route continued open, perhaps becoming more practicable, but that there was still no great stimulus or opportunity for migration over it. Such a stimulus came in the late Miocene, when faunal interchange increased very markedly. There was then certainly a fully practicable but still selective route. This increase in migration over a route that had probably been in existence but less used for some time previously may well be related to population expansions and shifts and consequent disequilibrium within Eurasia itself. There is evidence that the Miocene was a time of increasing movement within Eurasia and between Eurasia and Africa, with rapid expansion of some groups (such as the bovids in the southern areas) and crowding of others. That the intensified exchange with America may have been an indirect result of this internal Old World development is also suggested by the fact that at this time, even more than at others, the direction was predominantly from the Old World to the New. Except for this incursion, the North American fauna continued to evolve in an apparently orderly way.

PLIOCENE

As discussed above, the major and perhaps dual or multiple surge of migration around the Mio-Pliocene boundary was followed by a falling off of migration and then a new increase, with the exact dating of these events dependent on definitions of the epoch boundaries and formal arrangement of the data. The decline in intermigration sometime during the first half of the Pliocene may represent a breaking of the land route, too brief to be recorded (as the data are now arranged and in view of the inexact intercontinental correlations), in the form of complete stoppage of land migration. The mammalian evidence, however, does not rule out the possibility that the land route was open almost or quite continuously and that fluctuation in the frequency of migration across it resulted only from internal population factors on the two continents. In any case, if the route had been interrupted, it was again in existence and in active use by migrants before the end of the Pliocene.[14]

[14] It has long been recognized (*e.g.*, Smith, 1919; Grant and Gale, 1931) that the later Tertiary and Pleistocene marine invertebrates show an alternation of warm and cold waters along the Pacific coast of North America. It is probable that the sinking of the Bering bridge was followed by the southward extension of cold waters on this coast, and this may permit

PLEISTOCENE

This connection persisted throughout the early and middle Pleistocene and was definitively broken in the late Pleistocene. It may have oscillated, but if so the effect as far as the bridge, alone, was concerned was apparently not very different from that of continuous availability. It has been postulated that the lowering of sea level during glacial stages would expose the Bering route and the rise in interglacial stages would drown it. Details in that region are too poorly known to establish this clearly on geological grounds, and there is some reason to doubt it on faunal grounds. The glacial stages would appear to be just the times when long-range migration would be least effective, because the glaciers themselves would impede it. The faunal effects were felt as far away as southwestern Europe on one side and South America on the other and suggest free migration away from the abutment areas once the bridge was crossed. The glaciers in advancing would also tend to drive the prospective migrants away from the migration route, which was clearly in the far north although its direct abutments were probably not glaciated. It is more likely on several counts that the actual migration was mainly interglacial and that the migrants then retreated southward and spread out on each continent, with widespread effects on the whole continental fauna, especially during the glacial stages. The faunal oscillation is related more to the glaciation than to the bridge, and its phases may have been opposite to those demanded by glacial-stage connections and interglacial breaks. Here again, however, it must be remembered that the migration of record is usually a southward movement. Eastward or westward movement may have occurred in a preceding glacial stage within the relatively small area of the unglaciated bridgeheads, according to an interesting suggestion by R. M. Gilmore (1946, also an extensive unpublished manuscript which Gilmore kindly permitted me to read). Many complicated details remain to be worked out.

PLACES OF INTERCONTINENTAL CONNECTIONS

The basic problem regarding the positions of the land bridges used for these intercontinental migrations is whether they crossed the Atlantic or the Pacific. Early students, dealing mainly or exclusively with European and American faunas, naturally had their attention centered on the Atlantic and tended, explicitly or implicitly, to think of direct connections between North America and western Europe. It was, however, early recognized that there was a connection across the Pacific, or more specifically across Bering Sea or Strait, in the Pleistocene, at least. Matthew (1915), particularly, tended to emphasize this connection more and more; especially on the theoretical grounds that mammalian dispersal was in greatest part a radiation in all directions from central Asia. He came to interpret almost the whole of Eurasian-North American interchange in terms of such a bridge, alone, although in some, at least, of his work he also spoke of a very early Tertiary north Atlantic or Arctic connection directly between Europe and North America.

---

corroboration or more precise dating of the events suggested by the mammalian record. There are, however, other influences, some more local and some more widespread, that also affected the temperature of Pacific coastal waters, and such data as I have seen do not appear to be very exact or conclusive as regards the Bering bridge. I therefore confine my discussion to the mammalian evidence, with the hope that someone more competent than I in that field will revaluate the molluscan evidence on this point.

In Arldt's summary of early twentieth century opinion (Arldt, 1919–1922), a consensus favors the existence of both Atlantic and Pacific routes (intermittently) until the Miocene. For the Miocene and later, a consensus favors existence of the Pacific connection, while opinion on the Atlantic route is divided for the Miocene and Pliocene and opposed for the Pleistocene. Without taking a similar vote of later workers, it is fairly clear that the tendency has been to stress the Atlantic route for the early Tertiary and the Pacific route thereafter. That the early Cenozoic connection of North America was with Europe and that this was replaced, or first supplemented and then replaced, sometime during the Tertiary by a connection with Asia has become almost an article of faith to the supporters of continental drift, but they did not originate this idea, and it is probably now the majority opinion even among opponents of continental drift.

About the only concrete evidence for an early Tertiary Atlantic bridge or corridor is the unusually close similarity of early Eocene faunas in Europe and North America. On one hand, it is claimed that this similarity is too great to be explained by so long a land route as through Asia. On the other hand, it is argued that the similarity of these mysterious simultaneous incursions into the two regions requires dispersal from an intermediate point and that the movement to North America was therefore by the north Pacific or Bering route.

As a matter of fact, or of scientific reasoning, neither of these arguments is of any particular value. Close as was the early Eocene faunal relationship between western Europe and North America, it was little if any closer than for the Recent mammalian faunas of the same areas. This does not rule out an Atlantic bridge, but it shows that a Bering bridge could adequately account for all the facts. The Recent resemblance is almost certainly due to a Bering bridge, only. (This line of evidence is clearly opposed to continental drift—a point that I have discussed sufficiently elsewhere and that needs no special consideration here; *see* Simpson, 1943.) The opposite argument, for early Eocene dispersal both ways from Asia, has found no particular support in what is now known of Asiatic fossils. This explanation is not impossible, but it remains purely hypothetical and practically without force for the still more remote inference regarding the position of the early Tertiary bridge.

The needed direct evidence is knowledge of the early Eocene mammals of Asia, and especially of northeastern Asia. A few probably early Eocene forms have been found in Asia (*e.g.*, Young, 1934; Teilhard and Leroy, 1942), but so very few that they show only that some relationship with both Europe and America did exist, without really casting any light on the relative degree of relationship or, secondarily, the position of the bridge or bridges responsible for this. The only known Asiatic Paleocene fauna (Matthew, Granger, and Simpson, 1929) is of such peculiar facies that it certainly does not represent the source of the early Eocene migrants and casts little light on Paleocene continental relationships. It does suggest closer relationships with America than with Europe, but the evidence is quite insufficient for any reliance on this hint. The Cretaceous dinosaur faunas of central Asia are considered by Colbert (personal communication), who is now studying them, as more nearly related to American forms than are the European Cretaceous dinosaurs, and he concludes that the Cretaceous migration route was Pacific, not Atlantic. It will be shown below that the late Eocene route was probably also Pacific.

The general conclusion regarding the early Eocene route, and this applies about equally to possible Paleocene routes about which we know even less, is that there is insufficient evidence from the fossils of that time to permit an inference as to its location. Specifically, the evidence does not really support the reality of an Atlantic route, usually postulated. There is evidence that earlier (late Cretaceous) and later (late Eocene) routes were Pacific, and this would seem to establish some presumption that the early Eocene route was in the same general position, in the absence of any real indication to the contrary.

That the principal and probably only migration route for interchanges after the early Eocene was across some part of the Pacific or its northward extension can be established with probability, starting with the late Eocene. For subsequent interchanges the probability increases until it is virtually a certainty for the late Pliocene and Pleistocene.

The late Eocene is the earliest time for which known mammalian faunas suffice for some judgment of relationships and distribution within the Eurasian land mass. The fairly rich Shara Murun and Irdin Manha faunas of Mongolia (*see* Matthew and Granger, 1925a; 1925b; 1925c, scattered later American Museum publications, and faunal summary in Teilhard and Leroy, 1942) give an apparently fair representation of the mammals of central Asia and these are supplemented by a similar, but not identical, fauna in the Hoangho Valley (Young, 1937; Teilhard and Leroy, 1942). A small but significant fauna from Burma (Colbert, 1938) represents south Asia. Rich faunas are known in western Europe (Bartonian and Ludian) and western United States (Uintan, especially, and also the less rich Duchesnean, transitional to Oligocene). A summary of these faunas is given in Table 4.

Mention has been made of a north-south faunal differentiation in Eurasia in discussing the selective effect of climate. There was also clearly an east-west differentiation throughout the Tertiary, and this is well marked in the late Eocene. The Asiatic faunas of middle latitudes are distinctly different from those of Europe. For instance they include much more abundant and varied perissodactyls and fewer and less varied artiodactyls, not to mention differences of detail on lower taxonomic levels. In the late Eocene, the North American fauna resembles that of central Asia much more closely than it does that of Europe. For instance, 76 per cent of known central Asiatic families of that time occur also in America, but this is true of only 46 per cent of contemporaneous European families. Figures for genera, as now identified, are 17 and 8 per cent, respectively. The Asiatic fauna may be more nearly related to that of North America than to that of Europe although it is not surprising to find in it European elements absent from America. Moreover, almost all the known migrant groups of about this time are known from Asia, while many are unknown from Europe in spite of generally better knowledge of the European faunas. The apparent exceptions, like the Eomyidae, known from Europe and North America but not from Asia are so few and, as a rule, obscure that absence in Asiatic collections could obviously be due to lack of discovery.

Details are not necessary for present purposes, but mention should also be made of the rather extensive epeiric flooding of Europe during the Eocene and Oligocene. At times this flooding resulted in fragmentation of the dry land areas, and during parts of the early Tertiary central and eastern Asia and western Europe were ap-

TABLE 4.—*Known mammalian families, subfamilies, and genera in the late Eocene of North America (Uintan and Duchesnean), Central Asia (mainly Irdin Manha and Shara Murun), and Europe (Bartonian and Ludian)*

x Present
– Present earlier and later
e Present earlier
l Present later

	North America	Central Asia	Europe
Didelphidae	–		x
Didelphinae	–		x
Peratherium	–		x
Leptictidae	x		e
Protictops	x		
Erinaceidae	x		x
Echinosoricinae	x		x
Proterixoides	x		
Neurogymnurus			x
Soricidae	l		x
Soricinae	l		x
Saturninia			x
Talpidae	l		x
Talpinae			x
Amphidozotherium			x
Mixodectidae	x		
Craseops	x		
Adapidae	e		x
Adapinae			x
Pronycticebus			x
Anaptomorphidae	x		x
Omomyinae	x		e
Chumashius	x		
Dyseolemur	x		
Necrolemurinae			x
Necrolemur			x
Microchoerus			x
Pseudolorisinae			x
Pseudoloris			x
Apatemyidae	x		x
Stehlinella	x		
Heterohyus			x
Primates *inc. sed.*			
Yumanius	x		
Stylinodontidae	x		
Stylinodontinae	x		
Stylinodon	x		
Leporidae	x	x	l
Palaeolaginae	x	x	
Mytonolagus	x		
Shamolagus		x	
Gobiolagus		x	
Ischyromyidae	x	x	x
Paramyinae	x	x	x
Paramys	x	?	
Ischyrotomus	x		

TABLE 4—*Continued*

	North America	Central Asia	Europe
Leptotomus	x		
Plesiarctomys			x
Sciuravinae	x	l	
Sciuravus	x		
Cylindrodontinae	x	l	
Pareumys	x		
Aplodontidae	x		
Eohaplomys	x		
Protoptychidae	x		
Protoptychus	x		
Eomyidae	x		x
Eomys			x
Protadjidaumo	x		
Pseudosciuridae			x
Suevosciurus			x
Pseudosciurus			x
Sciuroides			x
Theridomyidae			x
Trechomys			x
Rodents *inc. sed.*			
Simimys	x		
Mesonychidae	x	x	e
Harpagolestes	x		
Hessolestes	x		
Andrewsarchus		x	
Oxyaenidae	e	x	x
Oxyaeninae	e	x	
Sarkastodon		x	
Hyaenodontidae	x	x	x
Proviverrinae	e	x	x
Quercytherium			x
Galethylax			x
Cynohyaenodon			x
Paracynohyaenodon		x	x
Hyaenodontinae	x	x	x
Propterodon		x	e
Pterodon	x	x	x
Hyaenodon	x	x	x
Limnocyoninae	x		x
Limnocyon	x		
Oxyaenodon	x		
Thereutherium			x
Machaeroidinae	x		
Apataelurus	x		
Creodont *inc. sed.*			
Paroxyclaenus			x
Miacidae	x	x	x
Viverravinae	x	l	x
Viverravus	e		x
Plesiomiacis	x		

TABLE 4—*Continued*

	North America	Central Asia	Europe
Miacinae	x	x	x
Uintacyon	x		
Miacis	x	x	x
Tapocyon	x		
Pleurocyon	x		
Canidae	x	1	x
Caninae	x	1	x
Procynodictis	x		
Cynodictis			x
Amphicynodontinae		1	x
Plesiocyon			x
Amphicyoninae			x
Pseudamphicyon			x
Viverridae			?
Stenoplesictis			?
Palaeoprionodon		1	?
Felidae	?		x
Proailurinae			?
Proailurus			?
Stenogale			?
Nimravinae	1		x
Ailurictis			x
Machairodontinae	?		1
Eosictis	x		
Hyopsodontidae	x		
Hyopsodontinae	x		
Hyopsodus	x		
Coryphodontidae	e	x	
Eudinoceras		x	
Pantolambdodontidae		x	
Pantolambdodon		x	
Uintatheriidae	x	x	
Eobasileus	x		
Gobiatherium		x	
Palaeotheriidae		e*	x
Pachynolophus			x
Propalaeotherium		e*	x
Lophiotherium			x
Anchilophus			x
Plagiolophus			x
Palaeotherium			x
Equidae	x	e*	e
Hyracotheriinae	x	e*	e
Epihippus	x		
Brontotheriidae	x	x	x
Dolichorhininae	x		
Metarhinus	x		
Mesatirhinus	x		
Sphenocoelus	x		
Dolichorhinus	x		

TABLE 4—*Continued*

	North America	Central Asia	Europe
Telmatheriinae	x	x	
Sthenodectes	x		
Metatelmatherium		x	
Desmatotitan		x	
Brontopinae	x	x	x
Manteoceras	x		
Epimanteoceras		x	
Protitan		x	
Microtitan		x	
Dolichorhinoides		x	
Gnathotitan		x	
Rhinotitan		x	
Packytitan		x	
Brachydiastematherium			x
Protitanotherium	x		
Teleodus	x		
Embolotheriinae		x	
Titanodectes		x	
Menodontinae	x		
Notiotitanops	x		
Diplacodon	x		
Eotitanotherium	x		
Chalicotheriidae	x	x	?, 1
Eomoropinae	x	x	
Eomoropus	x	x*	
Grangeria		x	
Isectolophidae	x		
Isectolophus	x		
Schizolophodon	x		
Helaletidae	x	x*	
Helaletinae	x	x*	
Heteraletes	x		
Diplolophodon		x*	
Colodontinae	—	x	
Desmatotherium	e	x	
Deperetella		x	
Teleolophus		x	
Inc. sed.			
Cristidentinus		x*	
Hyrachyidae	x	?	
Hyrachyus	x		
Hyracodontidae	x	x	
Triplopodinae	x	x	
Triplopus	x		
Caenolophus		x	
Hyracodontinae	x		
Mesamynodon	x		
Amynodontidae	x	x	1
Amynodon	x	x	
Megalamynodon	x		

TABLE 4—*Continued*

	North America	Central Asia	Europe
Amynodontopsis	x		
Rhinocerotidae	x		—
Caenopinae	x		—
Prothyracodon	x		
Dichobunidae	x		x
Dichobuninae	e		x
Dichobune			x
Mouillacitherium			x
Homacodontinae	x		
Bunomeryx	x		
Hylomeryx	x		
Sphenomeryx	x		
Mesomeryx	x		
Pentacemylus	x		
Choeropotamidae	x	x	x
Brachyhyops	x		
Gobiohyus		x	
Choeropotamus			x
Cebochoeridae			x
Cebochoerinae			x
Cebochoerus			x
Choeromorus			x
Mixtotheriinae			x
Mixtotherium			x
Entelodontidae	x	?, l	l
Achaenodontinae	x	?	
Achaenodon	x		
Anoplotheriidae			x
Catodontherium			x
Dacrytherium			x
Leptotheridium			x
Tapirulus			x
Anthracotheriidae	l	x	x
Haplobunodon			x
Thaumastognathus			x
Rhagatherium			x
Anthracosenex		x*	
Cainotheriidae			x
Oxyacron			x
Paroxacron			x
Agriochoeridae	x		
Protagriochoerus	x		
Mesagriochoerus	x		
Diplobunops	x		
Merycoidodontidae	x		
Protoreodontinae	x		
Protoreodon	x		
Hyomeryx	x		
Xiphodontidae			x
Dichodon			x

TABLE 4—*Concluded*

	North America	Central Asia	Europe
Xiphodon			x
Haplomeryx			x
Camelidae	x		
Poëbrotheriinae	x		
Protylopus	x		
Camelodon	x		
Poabromylus	x		
Amphimerycidae			x
Pseudamphimeryx			x
Hypertragulidae	x	x	
Archaeomerycinae	x	x	
Archaeomeryx		x	
Leptotragulus	x		
Leptoreodon	x		
Oromeryx	x		
Simimeryx	x		
Gelocidae		1	x
Phaneromeryx			x
Lophiomeryx		1	x
Cryptomeryx			x

* In China.

parently not united. The late Eocene faunal relationships are consistent with the view that eastern Asia and North America were then a continuous land area (although probably not broadly connected), separated on both sides from western Europe. It is, however, evident that the separation of Asia and Europe was incomplete, intermittent, or both, because faunal development in the two followed similar lines and reflects frequent interchange in spite of the local differences.

Only eleven genera of mammals are known in the Burmese late Eocene fauna. This fauna, again, is distinctive from that of central Asia or Europe, and it is likely that the distinction is in part, at least, regional and is not caused entirely by differences in facies or ecology. Closest relationship is with central Asia. Discounting facies and the chances of collecting, relationships to North America and to Europe may be about equal. Most important, from the present point of view, is that this fauna, as far as it goes, is less like the North American than are the Asiatic faunas from higher latitudes.

This evidence is admittedly not quite conclusive, but it is consistent and it definitely supports the conclusion that faunal interchange reflected in the late Eocene faunas was between Asia and North America, not directly between Europe and North America. It further, even though less strongly, suggests that the connection was more northern than southern in Asia. The data for this time, in themselves, permit no closer localization, but nothing opposes the possibility that the connection was at this time, as in the late Cenozoic, the Bering bridge. This is the most economical hypothesis, and, to anticipate slightly, I know of no valid evidence against

the view that all of the Eurasian-North American land faunal interchange in the Cenozoic was by way of this bridge.

Attention has been concentrated on the earliest interchange for which there is any real faunal evidence bearing on the location of the land bridge involved. The evidence is less complete for this than for succeeding epochs, and according to generally current ideas this, of the times for which there is evidence worth analyzing, is the time when a northern Pacific bridge is least likely or, at least, when a northern Atlantic bridge is most likely. This is important as a test case because the result is the same as for all succeeding major faunal interchanges: support of the north Pacific bridge as adequate in itself to explain the facts, and failure to find good evidence of a north Atlantic bridge.[15] The evidence is progressively better for the later interchanges, and since it all points in the same direction with increasing clarity its full presentation and analysis are unnecessary. It may be taken as established that later North American faunas are more closely related to those of central and eastern Asia than to those of Europe. It is, however, of interest to enquire further into faunal relationships within Asia, although on this point, too, a complete and continuous study of changes throughout post-Eocene times is not presented.

The Mio-Pliocene transition is a crucial point for faunal relationships, and some data on the Asiatic faunas of that time are given in Table 5. The Chinji and Nagri are the earliest relatively rich and well-known faunas from south of the Himalayas, which were rising at this time and beginning to be a decisive faunal barrier. Correlation is disputed, but the Chinji is either late Miocene or early Pliocene. The Nagri overlies the Chinji but is apparently very little later in geological age. Most of the genera and many of the species of the Nagri are the same as in the Chinji (*see* faunal lists in Colbert, 1935), and the distinction of the faunas may owe as much to a slight change in facies as to an appreciable evolutionary advance. The Tung Gur of Mongolia seems to be late Miocene and is near the Chinji in age but perhaps slightly older. The so-called Pontian or *Hipparion* faunas of China are widespread and probably, as recorded, cover a considerable span extending from the earliest Pliocene, if not even latest Miocene, into the middle Pliocene. They follow the Tung Gur in age and probably overlap the Nagri, perhaps even in part the Chinji, but also include somewhat later faunules (nearer the Indian Dhok Pathan in age). The list given in Table 5 for the Chinese "Pontian" is not complete but is representative, based on a limited number of occurrences probably of early Pliocene age. The American Barstovian (late Miocene) and Clarendonian (early Pliocene) lists are not given, but the occurrences in America at these times of groups common to the listed Asiatic faunas are noted. The Nagri and some of the Chinese "Pontian" may be post-Clarendonian, and later (mainly Hemphillian) North American occurrence of common elements with these faunas is therefore recorded by the symbol "l" under Clarendonian.

The Tung Gur and Chinese "Pontian" show no marked change of facies and represent successive faunas of a single faunal zone. Together, they show pronounced

[15] It has a bearing on evaluation of this opinion that I started this enquiry with the feeling that a north Atlantic bridge was probable in the Eocene and expected to find evidence of this. Possible subjectivity is reduced by failure to corroborate this prejudice.

TABLE 5.—*Families and genera of two South Asiatic and two Central Eastern Asiatic faunas, with record of occurrence in North America*

The North American faunas are not listed in their entirety, but only those families and genera that also occur among the four Asiatic faunas listed.

x Present
— Present both earlier and later
e Present earlier
l Present later

	Chinji	Nagri	Tung Gur	Chinese "Pontian"	North America	
					Barstovian	Clarendonian
Lorisidae	.....	x	.....	.....	.....	.....
Indraloris	.....	x	.....	.....	.....	.....
Pongidae	x	x	.....	.....	.....	.....
Dryopithecus	x	x	.....	.....	.....	.....
Sivapithecus	x	x	.....	.....	.....	.....
Hylopithecus	.....	x	.....	.....	.....	.....
Palaeopithecus	.....	x	.....	.....	.....	.....
Palaeosimia	x	.....	.....	.....	.....	.....
Sugrivapithecus	.....	x	.....	.....	.....	.....
Bramapithecus	x	.....	.....	.....	.....	.....
Ochotonidae	.....	.....	x	x	—	—
Ochotona	.....	.....	x	x	.....	l
Leporidae	.....	.....	.....	x	x	x
Alilepus	.....	.....	.....	x	.....	.....
Aplodontidae	.....	.....	.....	x	—	—
Pseudaplodon	.....	.....	.....	x	.....	.....
Castoridae	.....	.....	x	x	x	x
Amblycastor	.....	.....	x	.....	x	.....
Dipoides	.....	.....	.....	x	.....	l
Castor	.....	.....	.....	x	.....	l
Cricetidae	.....	.....	x	x	x	x
Prosiphneus	.....	.....	x	x	.....	.....
Paracricetulus	.....	.....	.....	x	.....	.....
Cricetulus	.....	.....	.....	x	.....	.....
Plesiodipus	.....	.....	.....	x	.....	.....
Gerbillus	.....	.....	.....	x	.....	.....
Rhizomyidae	x	—	.....	x	.....	.....
Pararhizomys	.....	.....	.....	x	.....	.....
?Rhizomys	x	.....	.....	x	.....	.....
Dipodidae	.....	.....	x	x	.....	.....
Protalactaga	.....	.....	x	x	.....	.....
Paralactaga	.....	.....	.....	x	.....	.....
Hystricidae	x	.....	.....	.....	.....	.....
Sivacanthion	x	.....	.....	.....	.....	.....
Hyaenodontidae	x	.....	.....	.....	e	.....
Dissopsalis	x	.....	.....	.....	.....	.....
Canidae	x	x	x	.....	x	x
Amphicyon	x	x	x	.....	.....	x
Vishnucyon	x	.....	.....	.....	.....	.....
Hemicyon	.....	.....	x	.....	x	.....
Gobicyon	.....	.....	x	.....	.....	.....
Procyonidae	x	x	.....	.....	x	x
Sivanasua	x	x	.....	.....	.....	.....
Mustelidae	x	—	x	x	x	x
Plesiogulo	.....	.....	.....	x	.....	l

TABLE 5—*Continued*

	Chinji	Nagri	Tung Gur	Chinese "Pontian"	North America	
					Barstovian	Clarendonian
Proputorius	.....	.....	.....	x	.....	.....
Melodon	.....	.....	x	x	.....	.....
Martes	x	.....	.....	.....	.....	]
Lutra	.....	.....	.....	x	.....	]
Eomellivora	x	.....	.....	.....	.....	.....
Sivalictis	x	.....	.....	.....	.....	.....
Vishnuonyx	x	.....	.....	.....	.....	.....
Viverridae	x	—	x	.....	.....	.....
Viverra	x	.....	.....	.....	.....	.....
Tungurictis	.....	.....	x	.....	.....	.....
Hyaenidae	x	x	x	x	.....	?,]
Ictitherium	]	]	.....	x	.....	.....
Hyaena	x	x	x	x	.....	.....
Lycaena	x	.....	.....	.....	.....	.....
Felidae	x	x	x	x	x	x
Metailurus	.....	.....	x	.....	.....	.....
Machairodus	.....	.....	x	x	.....	x
Vinayakia	x	x	.....	.....	.....	.....
Megantereon	.....	x	.....	.....	.....	.....
Sansanosmilus	x	.....	.....	.....	.....	.....
Paramachaerodus	x	—	.....	.....	.....	.....
Sivaelurus	x	.....	.....	.....	.....	.....
Vishnufelis	x	.....	.....	.....	.....	.....
Gomphotheriidae	x	—	x	x	x	x
Gomphotherium	x	—	.....	x	x	x
Tetralophodon	x	—	.....	x	e	.....
Serridentinus	x	.....	x	.....	x	x
Platybelodon	.....	.....	x	.....	.....	x
Anancus	x	—	.....	x	.....	.....
Syaconolophus	x	—	.....	.....	.....	.....
Mammutidae	.....	.....	.....	x	x	x
Mammut	.....	.....	.....	x	x	x
Elephantidae	x	—	.....	x	.....	]
Stegolophodon	x	—	.....	.....	.....	.....
Stegodon	.....	]	.....	x	.....	.....
Equidae	x	x	x	x	x	x
Anchitherium	.....	.....	x	.....	x	.....
Hypohippus	.....	.....	.....	x	x	x
Hipparion	x	x	.....	x	.....	x
Chalicotheriidae	x	x	x	x	e	.....
Macrotherium	x	x	x	.....	e	.....
Tapiridae	.....	.....	.....	x	—	—
Tapirus	.....	.....	.....	x	.....	]
Rhinocerotidae	x	x	.....	x	x	x
Chilotherium	x	x	.....	x	.....	.....
Gaindatherium	x	x	.....	.....	.....	.....
Aceratherium	x	x	.....	.....	.....	.....
Dicerorhinus	.....	.....	.....	x	.....	.....

TABLE 5—*Concluded*

	Chinji	Nagri	Tung Gur	Chinese "Pontian"	North America	
					Barstovian	Clarendonian
Tayassuidae	x	.....	.....	.....	x	x
Pecarichoerus	x	.....	.....	.....	.....	.....
Suidae	x	x	x	x	.....	.....
Palaeochoerus	x	x	.....	.....	.....	.....
Conohyus	x	x	.....	.....	.....	.....
Listriodon	x	x	x	.....	.....	.....
Lophochoerus	x	x	.....	.....	.....	.....
Propotamochoerus	x	x	.....	x	.....	.....
Dicoryphochoerus	x	x	.....	.....	.....	.....
Sanitherium	x	.....	.....	.....	.....	.....
Hippohyus	.....	x	.....	.....	.....	.....
Chleuastochoerus	.....	.....	.....	x	.....	.....
Sus	.....	.....	.....	x	.....	.....
Anthracotheriidae	x	x	.....	.....	.....	.....
Choeromeryx	x	—	.....	.....	.....	.....
Rhagatherium	x	.....	.....	.....	.....	.....
Anthracotherium	x	.....	.....	.....	.....	.....
Hyoboops	x	.....	.....	.....	.....	.....
Hemimeryx	x	x	.....	.....	.....	.....
Telmatodon	x	.....	.....	.....	.....	.....
Tragulidae	x	x	.....	.....	.....	.....
Dorcabune	x	x	.....	.....	.....	.....
Dorcatherium	x	x	.....	.....	.....	.....
Cervidae	x	—	x	x	x	x
Dicrocerus	x	.....	x	x	.....	.....
Stephanocemas	.....	.....	x	.....	.....	.....
Eostylocerus	.....	.....	.....	x	.....	.....
Cervocerus	.....	.....	.....	x	.....	.....
Procapreolus	.....	.....	.....	x	.....	.....
Lagomerycidae	.....	.....	x	.....	.....	.....
Lagomeryx	.....	.....	x	.....	.....	.....
Giraffidae	x	x	x	x	.....	.....
Palaeotragus	.....	.....	x	x	.....	.....
Samotherium	.....	.....	.....	x	.....	.....
Honanitherium	.....	.....	.....	x	.....	.....
Giraffokeryx	x	x	x	.....	.....	.....
Propalaeomeryx	x	.....	.....	.....	.....	.....
Giraffa	x	—	.....	.....	.....	.....
Bovidae	x	x	x	x	.....	.....
Antilospira	.....	.....	.....	x	.....	.....
Gazella	x	.....	.....	x	.....	.....
Pachygazella	.....	.....	.....	x	.....	.....
Urmiatherium	.....	.....	.....	x	.....	.....
Oioceros	.....	.....	x	.....	.....	.....
Sivoreas	x	.....	.....	.....	.....	.....
Sivaceros	x	x	.....	.....	.....	.....
Strepsiportax	x	.....	.....	.....	.....	.....
Pachyportax	.....	x	.....	.....	.....	.....
Helicoportax	x	.....	.....	.....	.....	.....
Selenoportax	.....	x	.....	.....	.....	.....

geographic differentiation from the Indian faunas. The latter are characterized by several groups that were poorly or not represented farther north at this time, notably the apes, anthracotheres, and tragulids. Other groups, notably the cats, proboscideans, pigs, giraffes, and bovids, are more abundant and varied in India, suggesting that they were primarily southern in origin and differentiation, but have certain restricted lines that extend into the northern faunas. The deer, most of the rodents, and perhaps some other groups seem to have the reverse relationship: more differentiated in the north with only a few lines reaching the southern regions.

In the course of a discussion of Mio-Pliocene faunas in Asia and North America, all of which is pertinent to the present outline of the same subject, Teilhard and Stirton (1934)[16] have commented on the "perfectly definite 'faunal sheet'" characteristic of the early Pliocene all over Eurasia and North Africa, adding that "differences occur, but they are due apparently to geographical causes." The large measure of uniformity in these faunas giving a distinct "Pontian aspect," recognizable in a glance at a collection or faunal list, has repeatedly been noted, to such an extent that the very real and even rather profound "differences . . . due . . . to geographical causes" have perhaps been underemphasized. Data like those presented here, but much more extensive, suggest that the Pontian "faunal sheet" consists in the main of a warm-climate Eurasian fauna that expanded vigorously at this time not only in the subtropics but also into temperate latitudes, where it mixed with but did not eliminate many groups formerly climatically and geographically distinct from it. Aside from the guide fossil, *Hipparion*, either immediately or ultimately of North American origin, most of the groups responsible for the "Pontian aspect" are typical of warmer climates and did not originate in or ever reach American unless belatedly and in the most highly attenuated form. The strong expansion of the Pontian fauna, as such, did not reach the intercontinental bridge, although it was doubtless an indirect factor in the migration around this time and later of other groups, contemporaneous but not Pontian as to faunal facies.

The groups of particularly Pontian aspect, responsible for the similarity of the faunal sheet over such a vast area, are mainly hyaenids, *Hipparion*, giraffes, and antelopes. It has been seen that the latter two groups were visibly attenuated even in still relatively low latitudes in China. Despite its abundance, *Hipparion* represents a single line of spectacularly successful invaders, not Eurasian autochthones like the vast majority of Pontian elements. The hyaenids were more, but not greatly, varied and were authochthones in this fauna, but they did (later if not at this time) succeed in adapting themselves to relatively cold and northern regions and (*fide* Stirton and Christian) did finally briefly appear in America.

In view of what has been said, it is not surprising to note that Table 5 shows a much closer relationship of the American with the Mongolian and Chinese faunas than with the Indian. It is perhaps surprising to note that the Chinese faunas are almost as closely related to the American as to the Indian. Judgment is not wholly based on these statistics, but the Tung Gur and Chinese "Pontian," combined, have 62 per cent of their families and 20 per cent of their genera in common with the Barstovian and Clarendonian and 62 per cent of their families and 23 per cent of their genera in

[16] For other important data on Pliocene faunas and faunal relationships in general, *see also* Stirton, 1935; 1939.

common with the Chinji and Nagri. The difference between the two comparisons is insignificant. This is the more striking in view of the fact that the Mongolian and Chinese areas are still a long distance from and far south of what is inferred to have been the actual abutment region of the bridge to America, its feeder and reception area, which was, in all probability, in extreme eastern Siberia.

These relationships are retained or accentuated in the Chinese faunas of the later Pliocene and Pleistocene or, for that matter, of the Recent. Certain "Pontian" and other southern elements persisted in what was and is for them a marginal position: a few murids, hyaenas (still abundant in the late Pliocene and Pleistocene of China), pigs (one line only, now fully at home in a cold temperate environment), a few antelopes, etc. The bulk of the faunas is, however, distinctly northern and has quite close over-all relationships with the American faunas of the same times.

In the Pleistocene for the first time good mammalian faunas are known from Siberia and Alaska. It is already well known that these, like the Recent faunas directly derived from them by differential extinction, are essentially different facies of a single fauna on the two continents. Siberian and Alaskan Pleistocene and Recent faunas differ rather less than the faunas of analogous life zones in eastern and western United States. Farther south on the two continents their faunas become progressively less similar, although even the extreme comparison of Patagonia with the East Indies shows a minimal but distinct resemblance, still harking back to the distant Siberian-Alaskan connection.

Precise and detailed studies of local faunal relationships in the Pleistocene and Recent in Siberia and Alaska have as yet barely been begun. They should cast a great deal of light on the doubtless intricate mechanism of faunal interchange in the region to which, as I now believe, it has been confined throughout the Cenozoic. These details are, however, aside from or, rather, additional to the broader problem set for this study. Enough evidence has been presented to demonstrate the probability that the Bering bridge was the only route involved in the Cenozoic interchanges.

FAUNAL RESEMBLANCE

Related to, but distinct from, the problems of faunal interchange and migration routes that have already been discussed is the question of faunal resemblance between Eurasia and North America. Faunas may agree or differ in various ways, such as over-all abundance, relative abundance of different faunal elements, ecological types represented and their relative abundance, diversity or numbers of different taxonomic groups included, etc. In the present study, however, attention will be concentrated on resemblance in taxonomic make-up, with the factors of diversity, abundance, and ecologic types minimized insofar as possible. In dealing, as in this paper, with problems of historical zoogeography, taxonomic resemblance is the most immediately significant basis of comparison, even though the other sorts of resemblances also have considerable importance.

The absolute data of taxonomic resemblance are the designated groups of mammals that the two regions have or had in common. As far as known, these are listed in sufficient detail in Table 1. (This table does not give the duration of common occurrence, which has also been tabulated but is not published here.) Further study

may be concerned not so much with the nature of the resemblance as with its degree. As far as determinable from the available faunas, this degree of resemblance can be measured by a proportion of groups at a given taxonomic level common to two areas to groups not common to the two. In selecting a measure of this type there are several alternatives, all of which may be derived from numerical values for N_1, the total number of known taxonomic units in the smaller fauna, N_2, this number for the larger fauna, and C, the number of units known to be common to both. The measure hitherto most frequently used has been $\frac{C}{N_1 + N_2 - C}$, that is, the fraction (usually given as a percentage) of common units in the total fauna of the two areas together.[17] A careful study of the characteristics of this and of several other measures has been made, but need not be presented in full here. It has been found that the measure $\frac{C}{N_1 + N_2 - C}$ is quite erratic and unreliable, especially as applied to paleontological data, and that the best simple measure of taxonomic resemblance, alone, is $\frac{C}{N_1}$, the fraction of common species in the smaller of the two faunas. This measure may conveniently be used in the form $\frac{100C}{N_1}$, which expresses it as a percentage or index and avoids the use of fractions. Possible values of $\frac{C}{N_1}$ vary from 0 to 1 and of $\frac{100C}{N_1}$ from 0 to 100. This measure minimizes the effects of differences in diversity and abundance and of unequal knowledge and chances of discovery, and tends, as nearly as any available simple measure, to approximate the real population value in spite of sampling fluctuations in the data.[18]

There are five main factors that influence taxonomic resemblance between two faunas: ecology, time, distance, connection, and source. Other things being equal in each case, the degree of taxonomic resemblance (and hence the value of $\frac{100C}{N_1}$) will vary (1) directly with the degree of ecological similarity between the two faunas, (2) inversely with the difference in age between the two faunas, (3) inversely with the geographic distance between the two faunas, (4) directly with the facility of communication between the two areas, (5) inversely with the extent of derivation of the two faunas from different sources.

---

[17] $(N_1 + N_2 - C)$ is the total number of separate units in the two faunas because the common units (C) occur in both. That is, if P_1 is the number peculiar to the smaller fauna, and P_2 the number peculiar to the larger, then $N_1 = P_1 + C$ and $N_2 = P_2 + C$. The total fauna of both is $P_1 + P_2 + C = N_1 + N_2 - C$.

[18] I have previously proposed the consistent use of this measure and exemplified it (Simpson, 1943). Without stating his source, Holmes (1944) quoted part of that paper and criticized some of my inferences based on use of this measure, on the grounds that the chances of finding fossils of any particular genus are so small that such comparisons must greatly underestimate the true proportion of genera common to two areas. There will, it is true, tend to be some underestimate if the chances of finding genera common to the two areas are definitely less than those of finding genera peculiar to one or the other, or if not merely one but both of the faunas being compared are poorly collected, and the actual number of specimens at hand for both of them is quite small so that most of the known common genera are represented in each by only one or two specimens. The first condition must be most unusual, if it ever really exists, and the second can be observed and discounted if it occurs. Usually at least one of the faunas compared has been well collected, and there is no reason why common genera should be consistently less frequently encountered than noncommon. In these, the usual conditions, Holmes' criticism has no force. Even though only a fraction of the genera that really existed in the two areas has been found, the value $\frac{100C}{N_1}$, for the known genera, will tend to approximate the true value for the original populations.

The last three relationships have much in common and may be confused, but there is a distinction. Even in a single land area with its faunules perfectly free to mingle and with all derived, in fact, from one source, complete homogeneity of fauna is seldom attained and in general more distant faunules will differ more—this is the third of the five relationships listed. On the other hand, any restriction on faunal interchange and any derivation of faunal elements from different sources will produce taxonomic differences between separate areas—these are the fourth and fifth relationships as listed.

Interesting as the first three of these relationships are, in themselves, it is the last two that are particularly pertinent in historical zoogeographical studies like this. The first three may, from this point of view, be influences that tend to obscure the relationship that is the main object of study. In dealing with fossil faunas, particularly, it is almost never possible to eliminate any of these relationships as of possible significance in influencing the observed degree of taxonomic resemblance. Two fossil faunas can seldom be determined to be exactly similar in ecology or of exactly the same age. The influence of distance is negligible only when comparing successive faunas in the same region.

A full discussion is outside the scope of this paper, but the analysis of these factors has some novel aspects for zoogeographic study, and they are so important that some special comment and examples are included even though not all bear directly on the topic of Eurasian and North American faunal resemblance.

A certain rather broad degree of ecological similarity is imposed by the definition of the problem in this and most similar studies. The data are derived from nonvolant land mammals, and all these belong to a single broad ecological category, varied as they may be in regard to smaller ecological divisions. Unless these smaller divisions are of the most diametrically opposed nature, the taxonomic differences between the faunas compared are likely to be strongly marked only on lower taxonomic levels, as of subspecies or species, and to decrease or become negligible on higher levels, as of genera or families. By and large, the mountains, forests, and steppes of a single region at one time will draw their mammals from the same families and will have a number of genera in common, but probably few species and perhaps no subspecies.

A paleontological example, on a small scale but still significant and interesting, is provided by middle Paleocene faunas in central Montana (data in Simpson, 1937). These occur in the same region and are of almost precisely the same geologic age, so that distance and time factors are negligible. Two faunules are from quarries and are closely similar in facies. Another fanule is from scattered surface finds, similar in facies among themselves but clearly distinct in facies from the quarries. The taxonomic resemblances are as follows:

$$\frac{100C}{N_1}$$

	Species	Genera	Families
2 quarries	73	86	100
Gidley quarry and surface localities	68	86	100

The influence of facies appears only in the figure for common species, and even here is slight. In general, such comparisons as have been made in quantitative form sug-

gest that with appropriate samples the influence of facies among faunas of nonvolant land mammals of the same age and from the same region is less pronounced than might be expected *a priori* and is generally less than and not well distinguished from the influence of minor differences of age, geographic separation, and chances of discovery.

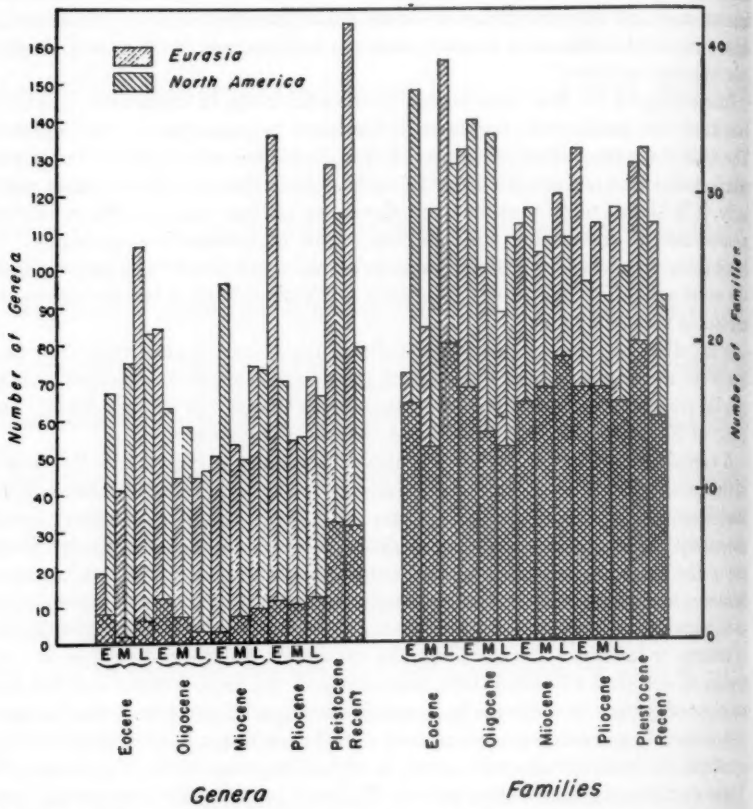


FIGURE 2.—*Absolute numbers of known genera and families of nonvolant land mammals peculiar to Eurasia or North America and common to both*

Looked at in another way, this means that this measure of taxonomic resemblance in faunas is not a good measure of ecological resemblance and not a particularly helpful approach in ecological studies, as applied particularly to fossil faunas in which data on the lowest taxonomic levels are seldom very good. In the above examples, the figures given would not warrant the conclusion that there is any appreciable difference in facies between the quarries and the surface localities. Data on the relative abundance of the different taxonomic groups show, however, that there is a very definite distinction between these facies. Ungulates and carnivores are relatively abundant at the surface localities and rare in the quarries. Primates and in-

sectivores are abundant in the quarries and almost absent at the surface localities. Ecological analysis, for its own sake, is most directly and hopefully approached by such study of relative abundance and not by that of taxonomic resemblance as here defined for a different purpose.

The same example may be extended to show how much more influence on this particular measure may result from geographic than from purely ecologic factors. The surface localities in Montana are rather closely similar in facies, as shown by relative abundance of the various ecological types, to the known fauna of the Torrejon formation in New Mexico, 650 to 700 miles distant. The age is nearly if not quite the same. $\frac{100C}{N_1}$ for species is 22, for genera 60, and for families 100.[19] The use of families is still too broad to reveal any difference in these generally similar faunas, but the figures for genera and species are much lower than for different facies in the same region. Of course it is impossible to rule out all influence of age and facies, but the major part of this difference appears to be basically geographic, and it is suggested that even in the middle Paleocene there was a distinct faunal zoning between southern and northern faunas in what is now the Rocky Mountain region of the United States.

The measure $\frac{100C}{N_1}$ is quite sensitive to lateral substitution of ecological vicars, a distributional or geographic rather than facial factor which is probably the strongest influence toward lower values of this measure in the example just given. It is frequently far less sensitive to more directly ecological differences, because it deliberately avoids indicating the presence in a more varied fauna of types absent in one less varied. For instance in the comparison of middle Paleocene faunules within Montana, the presence of many primates in the quarries and their absence at the surface localities is a very striking ecological indicator, but it makes no difference at all in the value of $\frac{100C.}{N_1}$ This emphasizes again that this measure is poor for primarily ecological studies but valuable for primarily geographic studies, the recommended use.

It must, however, be emphasized that use of this measure in this way depends on the suitability of the samples compared. With unsuitable samples, the differences summed up by $\frac{100C}{N_1}$ are still real, and the comparison is still valid, but it may not be the comparison intended. As with other statistical procedures, conclusions based on this measure do not flow automatically from the figures obtained but must take into consideration the characteristics of the samples and of the measure used. Also, as in all statistical methods, inferences from small samples relative to the population as a whole are less reliable than those from large samples. It is one of the advantages of this particular measure, used in the way here suggested, that it minimizes the defects of small samples and that it tends to minimize or eliminate purely facial differences, but it does so only under certain conditions.

The most important of these conditions are (1) that the larger of the two samples

[19] A reader of this manuscript, relatively unfamiliar with paleomammalogy, queried the correlation of faunas with so few species in common. Most species of mammals have such a short vertical range that even a few well-identified species in common usually indicate approximate contemporaneity. In this case, also, there are several phyla in the same evolutionary stage in the two deposits, even though represented by different (geographically differentiated) species.

(known parts of faunas) compared must be relatively large, including most or a considerable part of the whole fauna, and (2) that it must be either broadly representative of a large and regional fauna, not the strictly localized fauna of a narrow ecological niche, or must be similar in facies to or must include the facies of the smaller sample compared with it. These conditions are met in the comparisons that have been

TABLE 6.—*Taxonomic resemblances, measured by* $\frac{100C}{N_1}$ *for genera, between various late Paleocene faunas of the Rocky Mountain region*

(Genera queried are included. Table by Bryan Patterson.)

	Tiffany, surface	Tiffany, Mason Pocket	Tiffany, all	Plateau Valley	Bear Creek	Scarritt Quarry	Silver Coulee	Paskapoo	Clark Fork
Tiffany, surface	100	20	100	60	60	20	40	60	60
Tiffany, Mason Pocket	20	100	100	18	36	50	36	18	18
Tiffany, all	100	100	100	27	55	50	33	33	27
Plateau Valley	60	18	27	100	45	10	25	25	41
Bear Creek	60	36	55	45	100	20	27	18	45
Scarritt Quarry	20	50	50	10	20	100	50	30	10
Silver Coulee	40	36	33	25	27	50	100	50	19
Paskapoo	60	18	33	25	18	30	50	100	33
Clark Fork	60	18	27	41	45	10	19	33	100

discussed above, and they are met in the other comparisons to be made later in this section. By way of pointing the warning, however, what may happen when these conditions are not met is exemplified in Table 6, compiled by Bryan Patterson who has kindly permitted its publication here.[20]

Most of the samples involved in this table are small and are inadequately representative of the regional fauna. All are rather localized within a large area, and several are clearly from quite peculiar and narrowly restricted facies not comparable to each other and not included in the few larger samples. Most are sharply restricted as to age, but among them they cover a long span, although all late Paleocene. Under these conditions, in comparison of each sample with every other sample the differences due to facies, age, and geographic position are inextricably summed together, differences caused by facies tend to be exaggerated rather than minimized, and there is much random sample fluctuation—that is, accidental difference of the sample values from the real values for the original faunas in question. These are valid comparisons of the faunas as known, but they do not tend clearly to evaluate the regional and temporal differences of the areal faunas of that subepoch. They would tend to do so if the small samples were compared not each one with each other, but each with one good standard, were such available.[21] All together, even as they stand, they provide a good standard for comparisons with single or smaller faunas of other regions.

[20] Patterson, is, of course, well aware that these data exemplify use of $\frac{100C}{N_1}$ not directly comparable with its use elsewhere in this paper.

[21] The Silver Coulee will probably provide such a standard when fully described.

The influence of lapse of time is exemplified in an interesting way in Table 7, although these data do not isolate this factor from all others. $\frac{100C}{N_1}$ is given for genera in five successive late Paleocene to middle Eocene faunas in the Rocky Mountain region; the raw data are the faunal lists compiled by Van Houten (1945). The table clearly brings out a regular decrease in taxonomic resemblance of faunas in

TABLE 7.—*Taxonomic resemblances, measured by* $\frac{100C}{N_1}$ *for genera, between five successive mammalian faunas in the late Paleocene to middle Eocene of the Rocky Mountain region*

	Clark Fork	Gray Bull	Lysite	Lost Cabin	Bridger
Clark Fork	100	88	53	53	6
Gray Bull	88	100	94	66	21
Lysite	53	94	100	59	22
Lost Cabin	53	66	59	100	27
Bridger	6	21	22	27	100

either direction of the time dimension—that is, progressively smaller values of $\frac{100C}{N_1}$ starting at any fauna and running through either older or younger faunas. The table also brings out some irregularities not in the direction but in the degree of this change. These are probably due in part to unequal lengths of time involved in the different units, but also in part to factors other than lapse of time. For instance the Gray Bull resembles the immediately following Lysite more than it does the immediately preceding Clark Fork. This is probably due to difference in source (fifth of the influences listed on a previous page). The Gray Bull fauna is not wholly derived from the Clark Fork but includes a large immigrant element of different source, while the Lysite fauna is in larger measure derived from the Gray Bull or from the same sources as the Gray Bull. There is also some geographic influence, for the faunas are not all in the same region, although not far apart. Such differences in facies as may exist apparently do not influence most of these figures much, although this is probably one element in the unusually sharp separation of the Bridger from all preceding faunas.

Returning to the main theme of this paper, comparisons will be made first of all and mainly between the whole known Eurasian and North American faunas. The only omissions in this main sequence of comparisons are animals known exclusively from what is now the Oriental Region (already zoogeographically separable in the Eocene, as has been shown) in Eurasia and from what is now the Neotropical Region in North America, although Oriental and Neotropical elements that became incorporated in the faunas of middle latitudes are included after this incorporation. Comparison of such large units is rather gross, but it is necessary, in the present state of knowledge, if general trends are to be continuously followed. Where data are available, some comparisons of more limited areas will also be made, and relationships to the broader trend noted.

For most of the Tertiary either the known Eurasian and North American faunas are fairly similar ecologically or the larger of these covers an ecological range sufficient to minimize purely ecological effects on $\frac{100C}{N_1}$, which is stable if the ecological type of the smaller fauna is included in the larger and does not require that both should have the same ecological range. The apparent resemblance may nevertheless be somewhat lowered by ecological factors in some cases.

Comparison is intended to be of contemporaneous faunas each, however, covering a considerable time range in itself. It is certainly not true that the spans covered are exactly the same on the two continents. This, too, may have lowered the apparent resemblance, although this complication is to considerable extent counteracted by the fact that correlation is itself in large part based on faunal resemblance, tending to make apparent resemblances maximal in faunas correlated by this method.

Geographic separation is great throughout the broad comparison of Eurasia and North America. This certainly has a strong influence on the apparent resemblance of the faunas, making all the values of $\frac{100C}{N_1}$ certainly much lower than they would be if only adjacent parts of the two continents could be compared throughout, which is, of course, impossible because the faunas of these regions are not known in the Tertiary. The individual comparisons remain valid as defined, however, and apparent changes will correctly reflect real trends if faunas from the same regions, however distant, are used throughout. This is not strictly true of the main sequence to be presented for Eurasia, which includes practically only European faunas until the late Eocene and does not include well-distributed faunas across middle Eurasia until the late Miocene or Pliocene. Nevertheless there is some evidence that apparent fluctuations due to different geographical locations of successive faunas are not so great as real changes in continental faunal resemblance and do not wholly obscure the latter. The known American faunas are fairly unified in geographic position, from the point of view of such broad comparisons, before the Pleistocene. The influence of inclusion of northern faunas in the Pleistocene and Recent and some other geographic influences of the scattering of the data can to some extent be allowed for and will be discussed briefly.

The effect of facility of interchange between the two continents is one of the major factors being investigated. It clearly has had a strong influence on taxonomic faunal resemblance. However, neither in theory nor as observed is this relationship a simple one; for instance the resemblance is not a simple function of duration of a migration route but may even decrease while the migration route remains open. This involves an important series of special considerations to be briefly considered after the data have been presented.

As regards the last factor, source, there are also some peculiar elements in the present problem. Eurasia as here defined, or Holarctic Eurasia, exchanged faunal elements within itself, a more complex unit than North America, for instance in the Eocene when differentiation of a European and an Asiatic fauna seems to have been relatively great and to have resembled the relationship between two separate continents. This was apparently not true or less true in the middle and later Tertiary,

when this part of Eurasia had essentially a single continental fauna in spite of some rather pronounced local differences. But this continent also exchanged elements with southern Asia, zoologically ranking as a more or less separate continent, with Africa and with North America, during much if not all of the Cenozoic.

TABLE 8.—*Cenozoic faunal resemblance between Eurasia and North America*

Epoch		$\frac{100C}{N_1}$	
		Genera	Families
Recent		40	65
Pleistocene		28	63
Pliocene	Late	18	64
	Middle	18	68
	Early	16	71
Miocene	Late	12	63
	Middle	14	65
	Early	6	57
Oligocene	Late	7	59
	Middle	16	56
	Early	19	52
Eocene	Late	7	62
	Middle	5	62
	Early	42	89

North America, on the other hand, is a much smaller area and has been geographically and, as far as the known data show, faunally more unified throughout the Cenozoic. Furthermore, after the earliest Tertiary and until the late Pliocene, its mammalian fauna apparently had only two sources: North America, itself, and Asia. Since all the invading types during this time came through or from Asia, immigration into North America could promote only resemblance to Eurasia and not differences. Eurasia, on the other hand, drew immigrants from at least two major sources besides North America, and these could and did tend to reduce resemblance to North America. In the late Pliocene and Pleistocene North America received immigrants from another source, South America, but these never formed a very large proportion of the fauna, and they soon decreased to the present almost negligible figure.

Resemblance due to common source has a close relationship with the time element. The resemblance is instituted at the time of migration and thereafter tends to decrease with time, mere passage of time, with concomitant evolution of populations on each continent, having the same effect on faunal resemblance as if the common source were becoming more remote.

Table 8 presents the general sequence for Eurasia and North America as wholes (with the previously mentioned exceptions of strictly Oriental and Neotropical elements), and table 9 presents more scattered data involving more closely defined faunas. The data of Table 8 are presented graphically in Figure 3.

Taxonomic resemblances in families and in genera have some similarities, but also have striking differences. Both curves begin at a relatively very high point in the

early Eocene and then drop abruptly. The family curve reaches its low in the early Oligocene (dropping from 89 to 52) and then climbs irregularly to level off in the middle Miocene around a $\frac{100C}{N_1}$ value of about 65, which was thereafter maintained except for minor fluctuation, probably not significant except, possibly, for the slight,

TABLE 9.—*Taxonomic faunal resemblance of selected Central Eastern Asiatic and North American faunas*

Approximate age	Asiatic fauna	North American fauna	$\frac{100C}{N_1}$	
			Genera	Families
Recent	China and Mongolia	United States	18	52
Middle Pleistocene	Harbin	United States	58	75
Late Pliocene	"Sanmenian" ("Nihowan")	Blancan	16	58
Early Pliocene	Chinese "Pontian"	Clarendonian	11	62
Late Miocene	Tung Gur	Barstovian	17	53
Mid to Late Oligocene	Hsanda Gol	Orellan and Whitneyan	14	57
Early Oligocene	Ardyn Obo and Ulan Gochu	Chadronian	24	75
Late Eocene	Irdin Manha and Shara Murun	Uintan and Duchesnean	17	76

temporary rise in the early Pliocene. The generic curve drops still more rapidly to its low in the middle Eocene (5), then climbs to a secondary peak in the early Oligocene (19), drops more slowly to a late Oligocene and early Miocene low (6–7), then oscillates irregularly at a somewhat higher level (12–18) until it climbs very steeply in the Pleistocene and Recent to a high (40) not appreciably different from the early Eocene level.

Scattered data for the early Tertiary of Mongolia suggest that, if Asiatic faunas for this time were better known, the general Eurasian curves would not drop so far or so rapidly but would still have about the same trends except that the family low might be later, in the middle or late Oligocene, more nearly coincident with the second generic low.

The interpretation of this part of the curves can be related to the inferred faunal interchanges and migration routes with considerable probability and little complication. The intense early Eocene interchange, whatever its mysterious source, established a strong basic resemblance on all taxonomic levels above the species (these seem in every case to be different even in the early Eocene). Interruption of the migration route, which probably occurred before the end of the early Eocene and persisted until the beginning of the late Eocene, caused the faunas to evolve separately on the two continents, and this was the more marked because this was a time of rather rapid evolution among the progressive groups newly spread over the many local environments of the two continents. Resemblance declined rapidly, and this was more marked as regards genera which of course change more rapidly than do families.

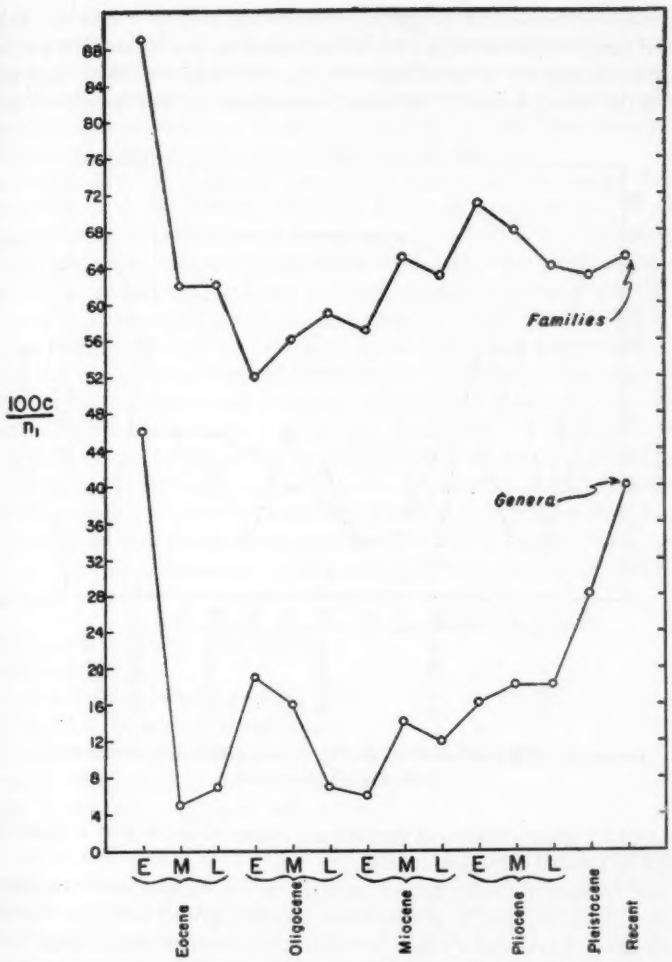


FIGURE 3.—*Taxonomic resemblance between known Eurasian and North American nonvolant land mammals*

Measured by $\frac{100C}{N_1}$ (*see* text) for families (above) and genera (below).

The late Eocene and early Oligocene interchange checked and reversed this trend as regards genera, but only slowed it down as regards families, not only because of their slower change but also because a large proportion of the families appearing separately on the two continents failed to migrate to the other. Another subsidence of the bridge, or at any rate practical cessation of interchange, in the middle and late Oligocene led to a second generic low. Probably the family low would occur here,

too, on a curve corrected for geographic distribution of known faunas. That the uncorrected family curve actually rises during this time can be ascribed not only to this probable inadequacy of knowledge but also to a negative rather than positive influence in the known faunas. Increasing resemblance in their families seems to be

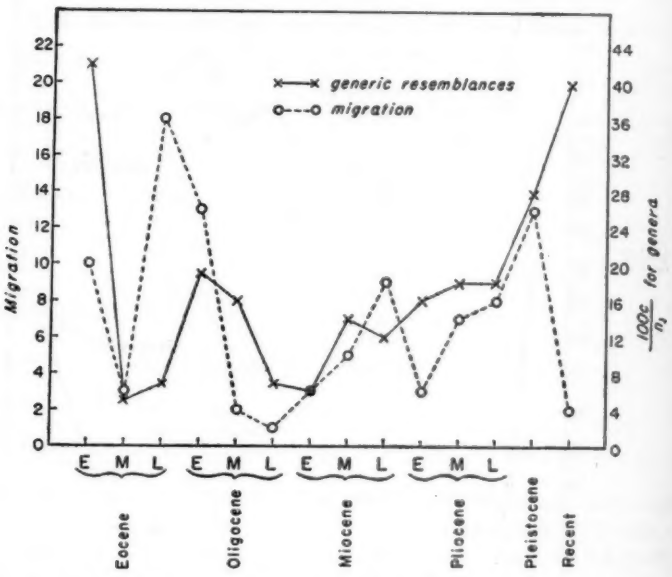


FIGURE 4.—*Migration curve (as in Fig. 1) and generic resemblance curve (as in Fig. 3) superposed*

caused rather by disappearance of families not common to the two regions than by appearance of families common to them.

The later Tertiary Eurasian faunas involved in the comparison are more widely and evenly distributed, and the general curve probably gives a fairly good representation for Holarctic Eurasia as a whole in this part of the sequence, although the minor fluctuations seen in the record cannot be considered reliable in detail. Particular Chinese faunas here tend to give figures somewhat, although not greatly, lower than for the broader comparison. The probable reason is that this region was during this time more strongly "infected" by Oriental elements, very few of which migrated to North America, than were other parts of Eurasia.

Continual interchanges during the later Tertiary brought the resemblance above the late Oligocene and early Miocene low, but it then tended to fluctuate around a moderate figure both for genera and for families. Basic differences in Eurasian and American faunas in the middle latitudes were well established, and the repeated interchanges, by way of the far North, tended to produce an equilibrium rather than an

indefinitely progressive increase in resemblance. Progressive evolution in America tended to produce a drift away from the Eurasian fauna, approximately compensated by moderate migration to Eurasia. In Eurasia there was not only this sort of drift, but also incursion of some African and Oriental groups; the equilibrium nevertheless was approximately maintained by the connected factor that more groups migrated from Eurasia to North America than in the opposite direction.

This equilibrium was apparently maintained without radical change through the Pleistocene and into the Recent. There probably was some real rise in generic resemblance, but the sharp rise shown by the generic curve is in part an artifact. The reason for this is that faunas of more northern regions, where most of the common genera now occur and had probably occurred throughout later if not all Tertiary times, are here known and included in the figures for the first time. This is reflected in the very high figures for the local Harbin fauna (about mid-Pleistocene), still some distance from the actual source and reception area for migrants but much nearer to it than Eurasia as a whole and relatively although not absolutely free of Oriental elements. Figures based on all of China and Mongolia in the Recent, on the other hand, fall below those for Holarctic Eurasia in general, because they do not include so many strictly boreal elements and do include a considerable Oriental infusion.

Even from these data, with all their imperfections, it is evident that intensity of faunal interchange and taxonomic resemblance are related without being completely correlated. Faunal interchange is only one of several factors involved in such resemblance:

Positive factors, increasing resemblance:
  Faunal interchange.
  Extinction of autochthones in either area.
Negative factors, decreasing resemblance:
  Progressive evolution and local differentiation in either area.
  Extinction of migrants in one area but not both.
  Faunal interchange of one area with a third.

All these factors are involved in the Eurasian-North American resemblance, and their separate contributions cannot easily be analyzed in the complex resultant, although the existence of such distinct contributions can be clearly seen at various points. Figures 5 and 6 represent diagrammatically the interplay of these theoretical factors in ways related to phases of Eurasian-North American faunal history.

Intensive faunal interchange is usually followed by some extinction of autochthones, although there may be sufficient lag to be geologically perceptible. It would, then, be expected from this relationship of the two positive factors that a peak in resemblance would tend to follow a peak in interchange, but not exactly. The data for genera in the Eurasian-North American interchange show sufficient agreement with this theoretical expectation. Interchange peaks in the late Eocene, late Miocene, and early Pleistocene are followed by more or less clear resemblance peaks in the Early Oligocene, early Pliocene (present in the curve, although not well marked or clearly significant), and late Pleistocene or Recent. In each case the picture is somewhat

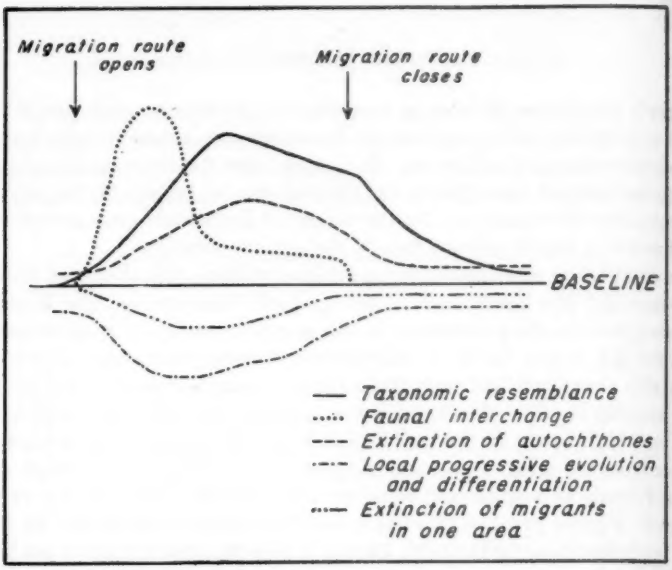


FIGURE 5.—*Theoretical and generalized diagram of the interplay of factors making for greater faunal resemblance (above base line) and those making for less (below base line) during one simple cycle of faunal interchange, with resultant changes in taxonomic resemblance between two areas involved in the interchange*

This sequence is closely approximated by the middle Eocene to late Oligocene relationships between Eurasia and North America. (*See* Figure 4.)

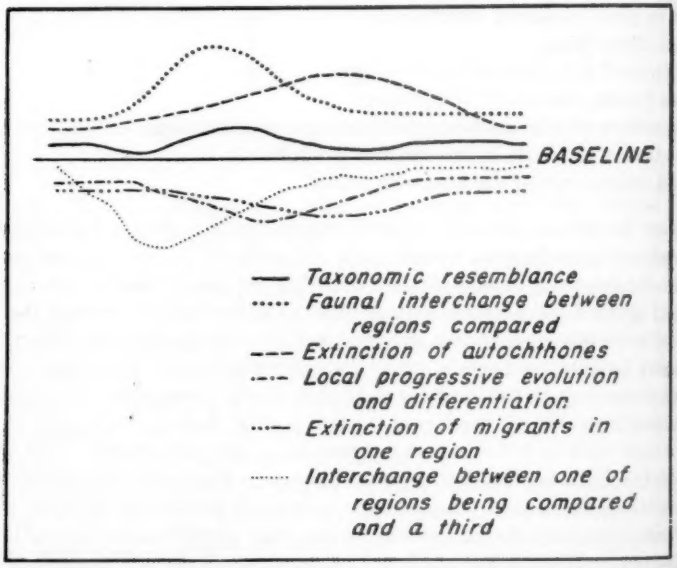

BASELINE
Taxonomic resemblance
Faunal interchange between regions compared
Extinction of autochthones
Local progressive evolution and differentiation
Extinction of migrants in one region
Interchange between one of regions being compared and a third

FIGURE 6.—*Theoretical and generalized diagram of interplay of factors making for more (above base line) or less (below base line) faunal resemblance between two regions, one of which also interchanges faunal elements with a third region, while the two regions are continually or continuously connected by a migration route*

The complex of factors as shown results in only minor fluctuation in taxonomic faunal resemblance of the two regions being compared. This pattern is approximated by the mid-Miocene to late Pliocene relationships between Eurasia and North America (Figs. 3, 4).

complicated by the fact that renewed, but apparently somewhat less intense, interchange coincided with the resemblance peak.

After an important interchange, resemblance will tend to decline as local differentiation and some extinction of migrants become dominant over the positive factors, which they tend to do even if some interchange continues, and of course do more rapidly if interchange ceases. This effect is clearly seen in the Eocene and again in the Oligocene, the only times during which interchange probably virtually ceased for any considerable span. In the later Cenozoic the various factors seem to be considerably more complex, and any clear separation is then impracticable. Holarctic Eurasia received a number of migrants from Africa and the Oriental region, tending toward less faunal resemblance with North America, but this in itself seems to have stimulated some renewed exchange, tending to increase faunal resemblance, when otherwise a more stable equilibrium in interchange would have existed with slow drift downward in resemblance because of progressive evolution and differentiation in each region.

SUMMARY

(1) Families, subfamilies, and genera of nonvolant land mammals common to Eurasia and North America are listed, with times of earliest known occurrence on each continent.

(2) The numbers of first known common occurrences on the two continents for each subepoch of the Cenozoic are tabulated. On the assumption that these numbers approximate the intensity of migration or faunal interchange at the given time, it is concluded that major interchanges have been in the early Eocene, late Eocene, early Oligocene, late Miocene, middle to late Pliocene, and Pleistocene, with weak interchange in the early and middle Miocene and early Pliocene, and very little or none in the middle Eocene and middle and late Oligocene.

(3) Direction of migration is discussed for each family concerned. The direction is unknown in many cases and doubtful in most, but some probabilities can be established.

(4) For each subepoch, lists are given of important migrants in either direction and of important nonmigrants of each region. There was apparently a tendency for migration to introduce progressively less distinctive types of animals in successive interchanges. Movement seems to have been predominantly from Eurasia to North America, and this may be correlated with selective factors in the faunal histories of the two regions.

(5) All the faunal interchanges were selective, and they apparently tended to become more selective as time went on. Not the only, but probably the most important, selective factor seems to have been climatic; the migrants generally are those groups tolerant of relatively cold climates.

(6) There may have been some shorter interruptions hardly discernible from their effects on the faunas, but the evidence suggests that there was an available land route between Eurasia and America continually if not continuously throughout the Tertiary except around the middle Eocene and middle to late Oligocene. There may also have been a briefer interruption during the first half of the Pliocene.

(7) All the faunal evidence is consistent with a single land route, the Bering bridge between Alaska and Siberia, as the sole means of mammalian interchange between Eurasia and America. Evidence is inadequate for the earliest Tertiary, but does not favor any other route, and from the late Eocene on increasingly strong evidence points to the Bering route.

(8) The measurement of taxonomic resemblance in faunas and the influence on it of various factors are discussed and exemplified. Fluctuations in resemblance for the land mammalian faunas of Eurasia and North America are followed throughout the Cenozoic and related tentatively to theoretical considerations. Factors increasing resemblance, interchange and extinction of autochthones, produced peaks of resemblance in the early Eocene and early Oligocene, doubtfully in the early Pliocene, and in the Pleistocene-Recent. Factors decreasing resemblance, localized evolution, extinction of migrants in only one of two regions, and migration into one from a third region, produced low points of resemblance in the middle to late Eocene and middle or late Oligocene. In the later Cenozoic there was some tendency for all five positive and negative factors to interact so as to produce minor fluctuation around a moderate level of resemblance.

REFERENCES CITED

Arldt, Th. (1919–1922) *Handbuch der Palaeogeographie*, 2 vols., Leipzig, Borntraeger.

Burke, J. J. (1936) Ardynomys *and* Desmatolagus *in the North American Oligocene*, Carnegie Mus., Ann., vol. 25, p. 135–154.

Chaney, R. W. (1940) *Tertiary forests and continental history*, Geol. Soc. Am., Bull., vol. 51, p. 469–488.

Colbert, E. H. (1935) *Siwalik mammals in the American Museum of Natural History*, Am. Philos. Soc., Tr., n. ser., vol. 26, p. i–x, 1–401.

——— (1937) *The Pleistocene mammals of North America and their relations to Eurasian forms*, in *Early man*, edited by G. G. MacCurdy, New York, Lippincott, p. 173–184.

——— (1938) *Fossil mammals from Burma in the American Museum of Natural History*, Am. Mus. Nat. Hist., Bull., vol. 74, p. 255–436.

Depéret, C. (1905) *L'évolution des mammifères Tertiaires; importance des migrations (Éocène)*, Acad. Sci. Paris, C. R., vol. 141, p. 702.

——— (1906a) *L'évolution des mammifères Tertiaires; importance des migrations (Oligocène)*, Acad. Sci. Paris, C. R., vol. 142, p. 618.

——— (1906b) *L'évolution des mammifères Tertiaires; importance des migrations (Miocène)*, Acad. Sci. Paris, C. R., vol. 143, p. 1120.

——— (1907) *Les transformations du monde animal*, Paris, Flammarion.

Frick, C. (1937) *Horned ruminants of North America*, Am. Mus. Nat. Hist., Bull., vol. 49, p. i–xviii, 1–669.

Furon, R. (1941) *La paléogéographie*, Paris, Payot.

Gilmore, R. M. (1946) *Arctic mammalogy*, in *A program of desirable scientific investigations in Arctic North America*, Arctic Inst. N. Am., Bull. 1, p. 35–43.

Grant, U. S., IV, and Gale, H. R. (1931) *Catalogue of the marine Pliocene and Pleistocene Mollusca of California and adjacent regions*, San Diego Soc. Nat. Hist., Mem., vol. 1, p. 1–1036.

Gregory, J. W. (1930) *The geological history of the Pacific Ocean*, Geol. Soc. London, Quart. Jour., vol. 86, p. lxxii-cxxxvi.

Holmes, A. (1944) *Principles of physical geology*, London, Thomas Nelson and Sons.

Joleaud, L. (1939) *Atlas de paléobiogéographie*, Paris, Lechevalier.

Lydekker, R. (1896) *A geographical history of mammals*, Cambridge, Cambridge Univ. Press.

Matthew, W. D. (1915) *Climate and evolution*, New York Acad. Sci., Ann., vol. 24, p. 171–318.

——— and Granger, W. (1925a) *New creodonts and rodents from the Ardyn Obo formation of Mongolia*, Am. Mus. Novitates, no. 193, p. 1–7.

——— — ——— (1925b) *New ungulates from the Ardyn Obo formation of Mongolia*, Am. Mus. Novitates, no. 195, p. 1–12.

——— — ——— (1925c) *New mammals from the Shara Murun Eocene of Mongolia*, Am. Mus. Novitates, no. 196, p. 1–11.

——— Granger, W., and Simpson, G. G. (1929) *Additions to the fauna of the Gashato formation of Mongolia*, Am. Mus. Novitates, no. 376, p. 1–12.

Mayr, E. (1941) *Wanderung oder Ausbreitung?* Zoogeog., vol. 4, p. 18–20.

——— (1946) *History of the North American bird fauna*, Wilson Bull., vol. 58, p. 3–41.

McGrew, P. O. (1944) *An early Pleistocene (Blancan) fauna from Nebraska*, Field Mus. Nat. Hist., geol. ser., vol. 9, p. 33–66.

Osborn, H. F. (1910) *The age of mammals in Europe, Asia, and North America*, New York, Macmillan.

Pilgrim, G. E. (1939) *The fossil Bovidae of India*, Paleont. Indica, n. ser., vol. 26, Mem. 1, p. i–iii, 1–356.

Sclater, W. L., and Sclater, P. L. (1899) *The geography of mammals*, London, Kegan Paul, Trench, Trübner.

Scott, W. B., and Jepsen, G. L. (1936) *The mammalian fauna of the White River Oligocene—Part I. Insectivora and Carnivora*, Am. Philos. Soc., Tr., vol. 28, p. 1–153.

Simpson, G. G. (1937) *The Fort Union of the Crazy Mountain Field, Montana, and its mammalian faunas*, U. S. Nat. Mus., Bull. 169, p. i–x, 1–287.

——— (1940) *Mammals and land bridges*, Washington Acad. Sci., Jour., vol. 30, p. 137–163.

——— (1942) *The beginnings of vertebrate paleontology in North America*, Am. Philos. Soc., Pr., vol. 86, p. 130–188.

——— (1943) *Mammals and the nature of continents*, Am. Jour. Sci., vol. 241, p. 1–31.

——— (1945) *The principles of classification and a classification of mammals*, Am. Mus. Nat. Hist., Bull., vol. 85, p. i–xvi, 1–350.

Smith, J. P. (1919) *Climatic relations of the Tertiary and Quaternary faunas of the California region*, Calif. Acad. Sci., Pr., ser. 4, vol. 9, p. 123–173.

Stirton, R. A. (1936) *Succession of North American continental Pliocene mammalian faunas*, Am. Jour. Sci., vol. 32, p. 161–206.

——— (1939) *Significance of Tertiary mammalian faunas in holarctic correlation with especial reference to the Pliocene of California*, Jour. Paleont., vol. 13, p. 130–137.

——— and Christian, W. G. (1940) *A member of the Hyaenidae from the upper Pliocene of Texas*, Jour. Mammal., vol. 21, p. 445–448.

Teilhard de Chardin, P. and Leroy, P. (1942) *Chinese fossil mammals*, Inst. Géo-Biol. Pékin, [Bull.] no. 8, p. 1–142.

——— — Stirton, R. A. (1934) *A correlation of some Miocene and Pliocene mammalian assemblages in North America and Asia with a discussion of the Mio-Pliocene boundary*, Univ. Calif. Pub., Bull. Dept. Geol. Sci., vol. 23, p. 277–290.

Van Houten, F. B., (1945) *Review of latest Paleocene and early Eocene mammalian faunas*, Jour. Paleont., vol. 19, p. 421–461.

Young, C. C. (1934) *A review of the early Tertiary formations of China*, Geol. Soc. China, Bull., vol. 13, p. 469–503.

——— (1937) *An early Tertiary vertebrate fauna from Yuanchü*, Geol. Soc. China, Bull., vol. 17, p. 413–438.

American Museum of Natural History and Columbia University, New York, N. Y.

Manuscript Received by the Secretary of the Society, February 26, 1947